

# Searches for Higgs bosons with tau leptons

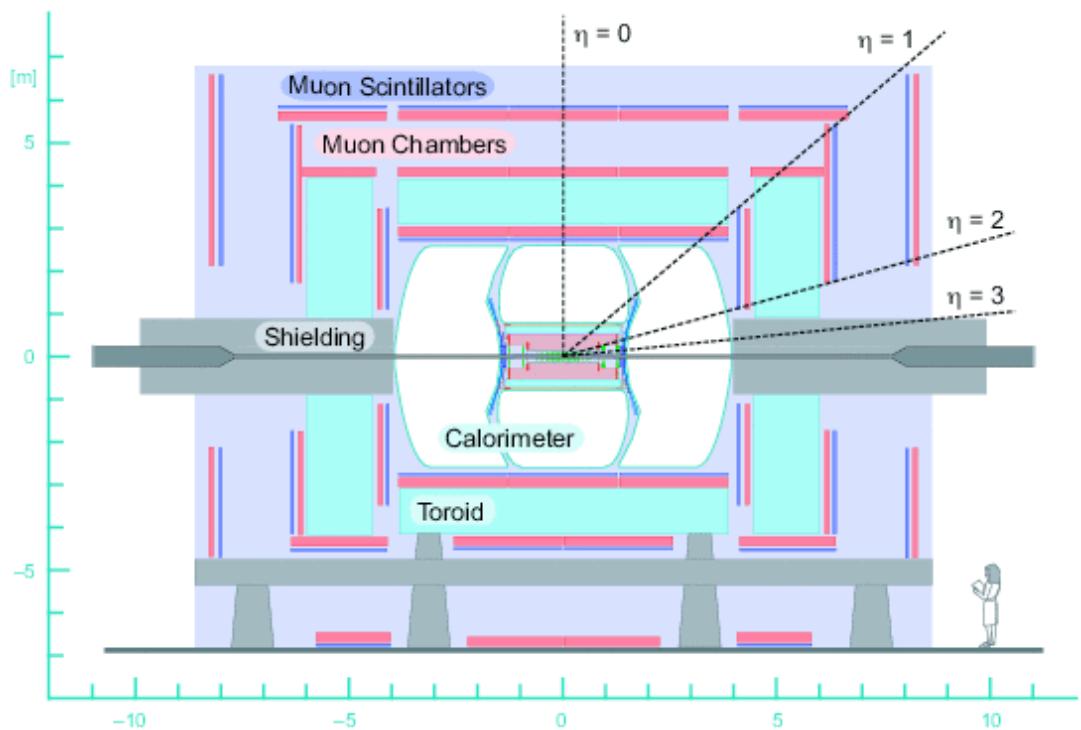
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University of Manchester

# Outline

- The DØ detector
- Higgs beyond the SM
- Search for doubly charged Higgs bosons
- Search for SM Higgs boson
- Conclusions

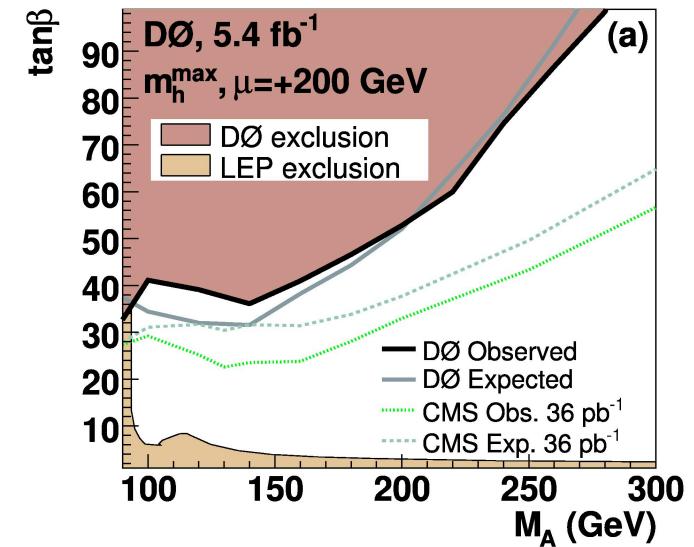
# The DØ detector

- General purpose detector
- Central Trackers
  - SMT (silicon tracker)
  - CFT (fiber tracker)
- EM and hadronic calorimeters
- Muon system
- Two magnets (solenoid and muon toroid)



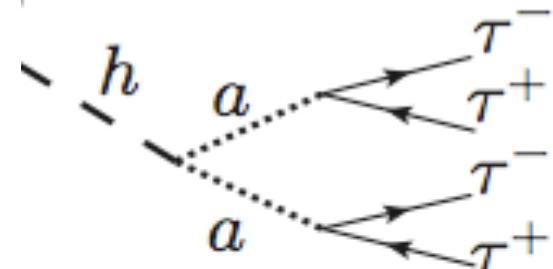
# Higgs beyond the Standard Model

- Beyond the SM models often have extended particle content and Higgs sector
  - Example: Supersymmetry solves hierarchy problem by introducing a new symmetry between bosons and fermions
  - Minimal version (MSSM) has two Higgs doublets, leading to extended Higgs sector with 5 Higgs bosons.
  
- Enhanced coupling to down type quarks and leptons
- Main decay channels,  $\phi = (h, H, A)$ 
  - $BR(\phi \rightarrow bb) \sim 90\%$
  - $BR(\phi \rightarrow \tau\tau) \sim 10\%$



# Higgs beyond the SM

- The Next-to-Minimal-Supersymmetric Standard Model (NMSSM) extends MSSM by a Higgs singlet, leading to 7 Higgs bosons
- 3 scalar Higgs,  $h_i$ , 2 pseudo-scalar,  $a_i$ , and a charged Higgs  $H^\pm$
- Project undertaken to implement NMSSM into **HERWIG++** MC generator – arXiv:1102.1672 [hep-ph]
  - **HERWIG++** collaboration member
- Theory predicts  $h \rightarrow aa \rightarrow 4\tau$ , maybe the dominant SM like-Higgs boson decay (difficult experimentally since tau leptons have low  $p_T$ )



# A search for the doubly charged Higgs boson at DØ

# Doubly charged Higgs appear in numerous extension to the SM with Higgs doublets or triplets

- Left-right symmetric models
  - Predict new symmetry between left and right handed particles.
  - Introduce new heavy right handed bosons and right handed neutrino.
  - Extended Higgs sector predicts both left and right handed  $H^{\pm\pm}$ , where the handedness refers to the particles it couples to.

# Doubly charged Higgs appear in numerous extension to the SM with Higgs doublets or triplets

- Little Higgs models
  - Fix hierarchy problem.
  - Predict new heavy gauge bosons,  $W_H$  and  $Z_H$ , a heavy quark pair and new Higgs bosons, including doubly charged Higgs bosons.
  - The coupling of the  $H^{\pm\pm}$  boson to leptons depends on the ratio of the Yukawa couplings, as measured in neutrino oscillation measurements.
  - Assuming the normal hierarchy and a very small mass for the lightest neutrino ( $< 10\text{meV}$ ), then the decay of  $H^{\pm\pm}$  bosons to electrons can be neglected and  $B(H^{\pm\pm} \rightarrow \tau\tau) = B(H^{\pm\pm} \rightarrow \mu\mu) = B(H^{\pm\pm} \rightarrow \tau\mu) = 1/3$ .

# Doubly Charged Higgs at the Tevatron

## Production mechanisms

$$p\bar{p} \rightarrow Z/\gamma^* \rightarrow H^{++}H^{--},$$

$$p\bar{p} \rightarrow W^\pm \rightarrow H^{\pm\pm}H^\mp,$$

$$p\bar{p} \rightarrow W^\pm W^\pm \rightarrow H^{\pm\pm}$$

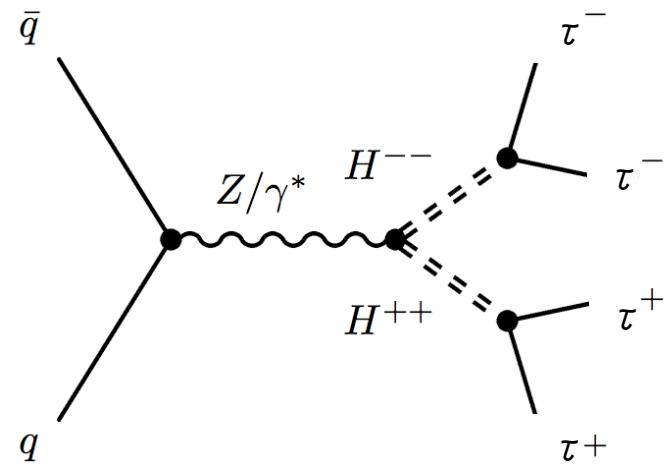
- $H_{_R}^{\pm\pm}H_{_R}^{\pm\pm}$  cross section a factor of 2 smaller than for  $H_{_L}^{\pm\pm}H_{_L}^{\pm\pm}$ .
- The  $H^{\pm\pm}H^\pm$  channel depends on assumptions about  $H^\pm$  (therefore not considered here).
- Existing phenomenological and theoretical constraints favour coupling of  $W^\pm W^\pm$  to  $H^{\pm\pm}$  to vanish.

# Doubly Charged Higgs at the Tevatron

## Decay mechanisms

$$H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm$$

- Assume decays to leptons dominate (violates lepton number).
- No previous search for  $H^{\pm\pm}$  decaying into tau leptons at a hadron collider



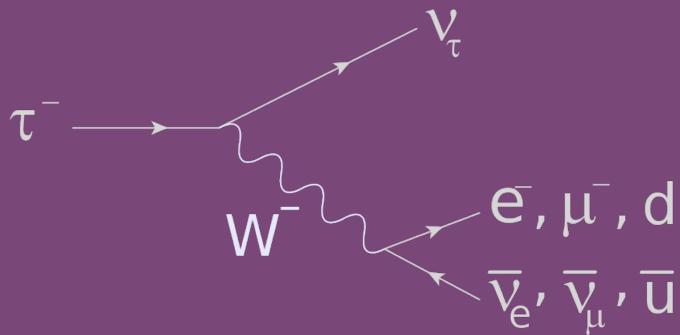
# Analysis Overview

- Search for  $H^{\pm\pm}$  decaying to  $\mu\mu, \mu\tau, \tau\tau$
- First search at hadron collider to  $\tau\tau$
- Total integrated luminosity of  $7.0 \text{ fb}^{-1}$
- Limits on the cross section set for different benchmark points
- Search for  $M(H^{\pm\pm}) = 100 \text{ to } 200 \text{ GeV}$ , as below this range excluded by LEP

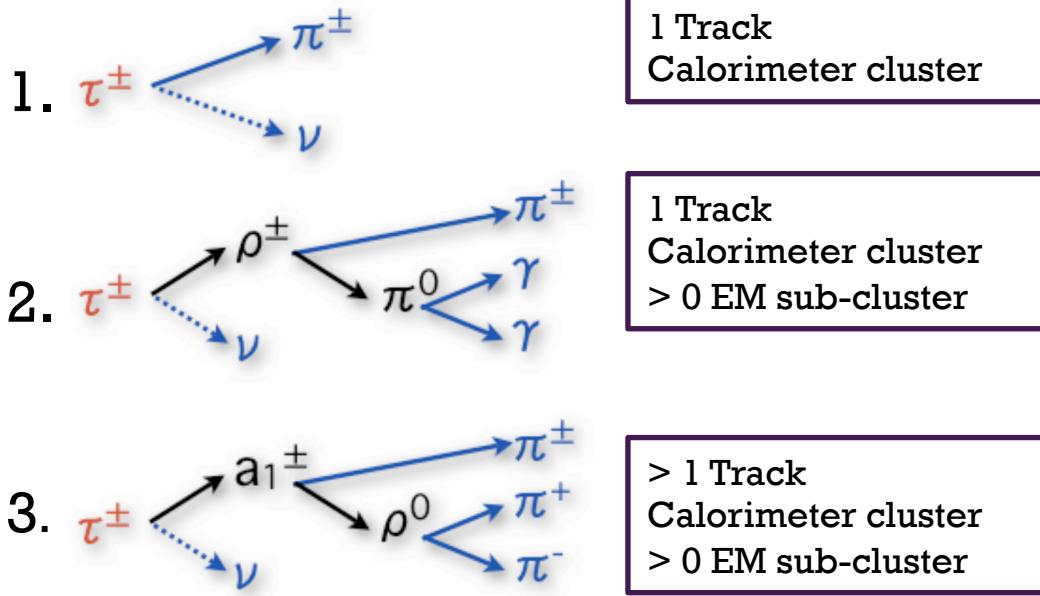
# The benchmark points

1.  $H^{\pm\pm}$  decaying to tau leptons,  $B(H^{\pm\pm} \rightarrow \tau\tau) = 1.$
2. Mixed branching ratio to tau leptons and muons,  
 $B(H^{\pm\pm} \rightarrow \tau\tau) + B(H^{\pm\pm} \rightarrow \mu\mu) = 1.$
3.  $H^{\pm\pm}$  decaying to muons,  $B(H^{\pm\pm} \rightarrow \mu\mu) = 1.$
4.  $H^{\pm\pm}$  decaying to tau lepton/muon pairs,  $B(H^{\pm\pm} \rightarrow \tau\mu) = 1.$
5. The Little Higgs model specific decay mode:  
 $B(H^{\pm\pm} \rightarrow \tau\tau) = B(H^{\pm\pm} \rightarrow \mu\mu) = B(H^{\pm\pm} \rightarrow \tau\mu) = 1/3.$

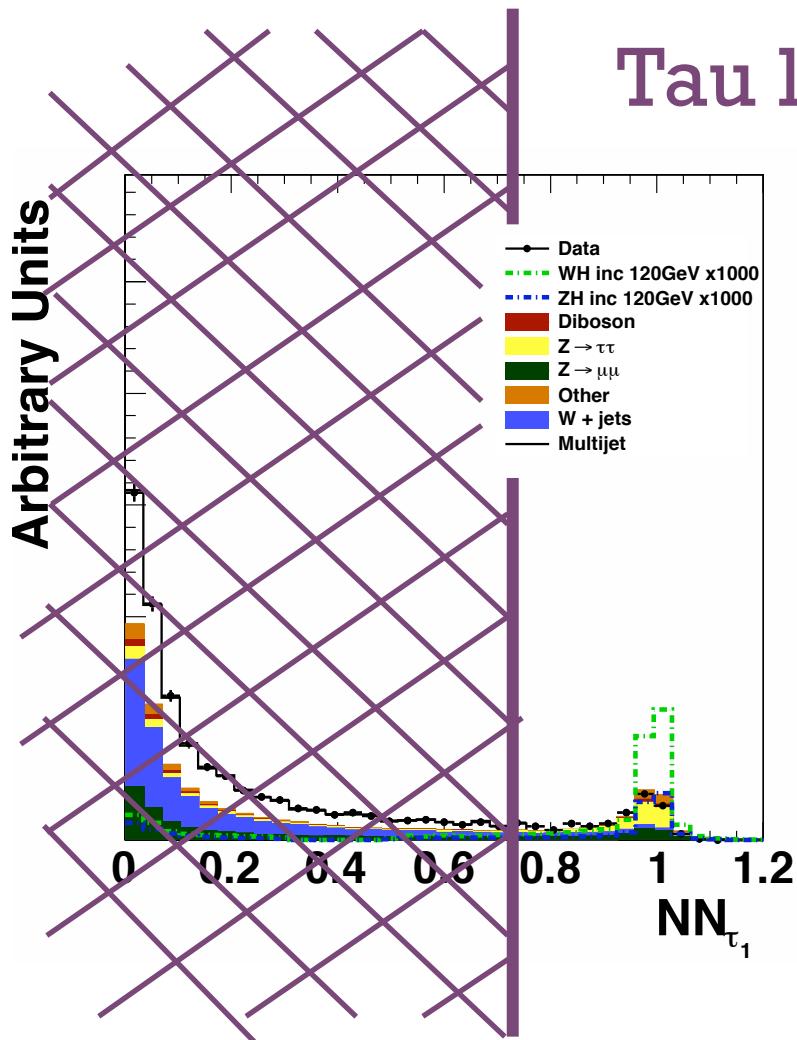
# Tau lepton identification at DØ



- Leptonic tau decays to  $e$ ,  $\mu$  are treated like all other electrons and muons.
- Specific tools for hadronically decaying tau leptons.
- Low multiplicity jets easily mis-identified as hadronic tau decays.



## Tau lepton Neutral Network



- Trained on 10-12 variables, depending on tau type
- Trained on sample of  $Z \rightarrow \tau\tau$  for data and MC

Responsible for certification of the Run IIb3 data and certification of new Neural Network

# General event selection

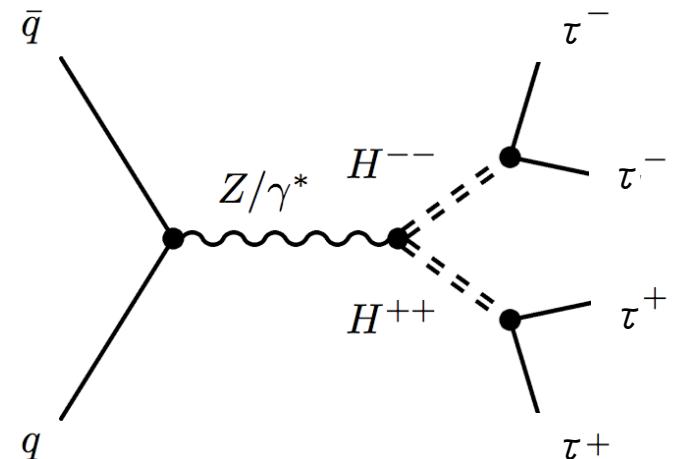
Applied to the two selected hadronic taus  
and the selected muon

## Tau Selection

- $|\eta| < 1.5$
- $p_T > 12.5/12.5/15 \text{ GeV}$  for Type-1/-2/-3
- Tracks must pass ‘Loose’ quality criteria
- $\Delta R(\tau_i, \mu) > 0.4$  for all muons that pass ‘Loose’ selection

## Muon Selection

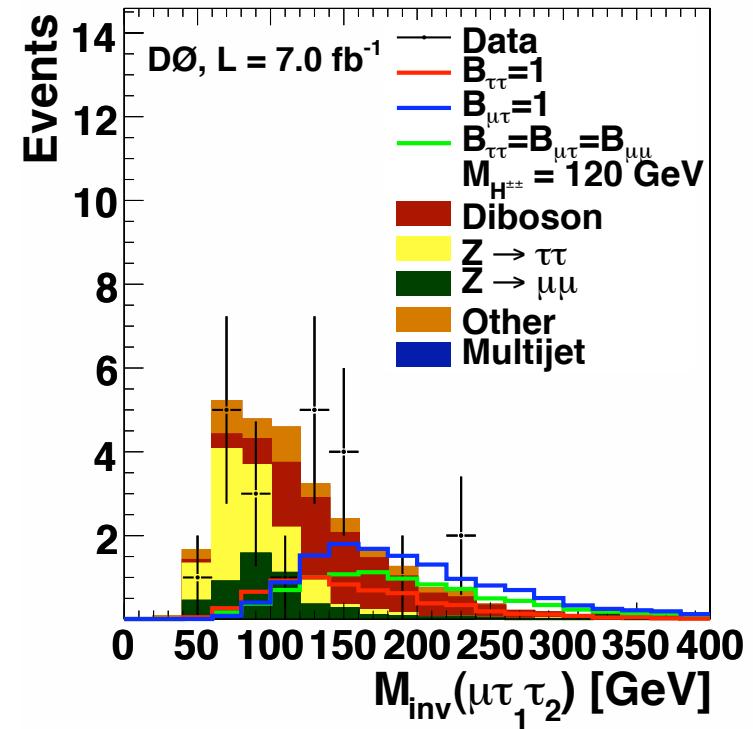
- In order for trigger efficiencies to be applicable
  - $p_T > 15 \text{ GeV}$
  - $|\eta| < 1.6$



# Event selection

Applied to the two selected hadronic taus  
and the selected muon

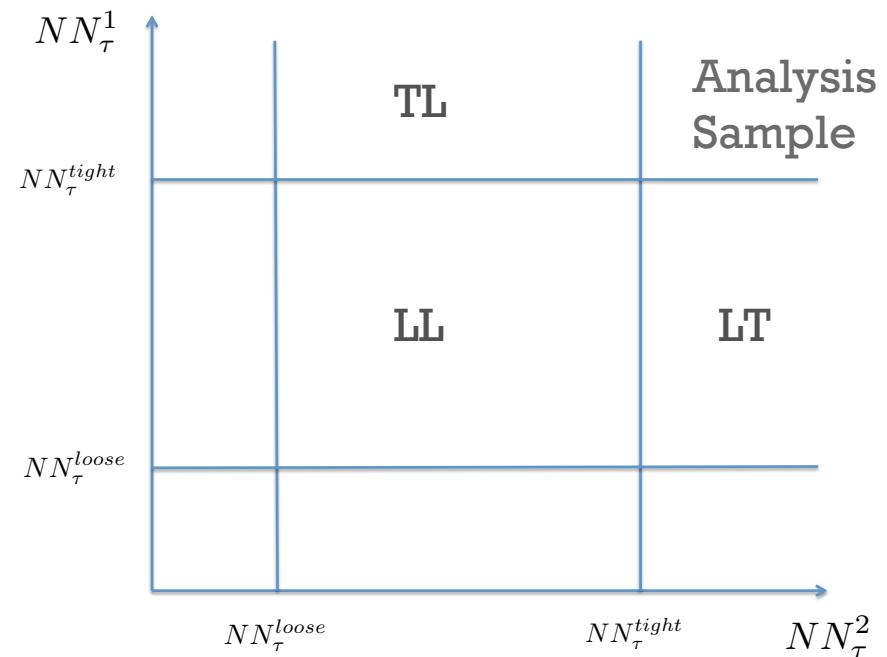
- Only Type-1 and Type-2 tau leptons (1-prong)
- $\Delta R > 0.5$  between leading tau leptons and leading muon
- $\Delta R > 0.7$  for two leading tau leptons
- $NN > 0.75$  for all tau types
- All leptons from common vertex
- $|Q| = |q_1 + q_2 + q_3| = 1$
- Do not veto on extra leptons



# Instrumental background (jets)

## Data driven methods

- Expect contribution from jets misidentified as hadronically decaying tau leptons
- Define 3 samples, orthogonal to analysis sample
- Samples defined based on tau lepton Neural Network requirement

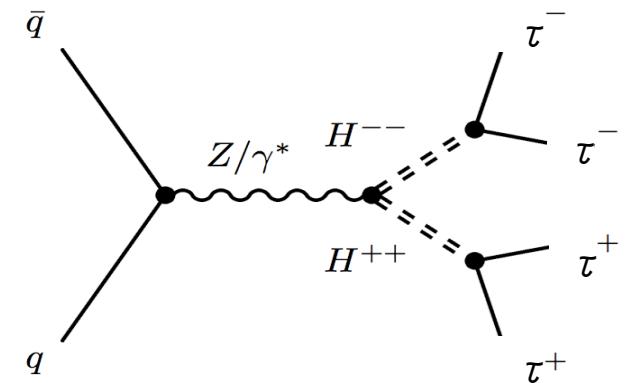


$$N^{IB} = \epsilon_{LT}\epsilon_{TL}(N_{LL}^{data} - N_{LL}^{MC})$$

# Discriminating channels

Separate events into four samples, depending on whether the two tau leptons originate from same or from different Higgs bosons.

- TT channel:  $N_\tau = 2, N_\mu = 1, q(\tau_1) = q(\tau_2)$
- TM channel:  $N_\tau = 2, N_\mu = 1, q(\tau_1) \neq q(\tau_2)$
- T3 Channel:  $N_\tau = 3, N_\mu = 1$
- M2 Channel:  $N_\tau = 2, N_\mu = 2$

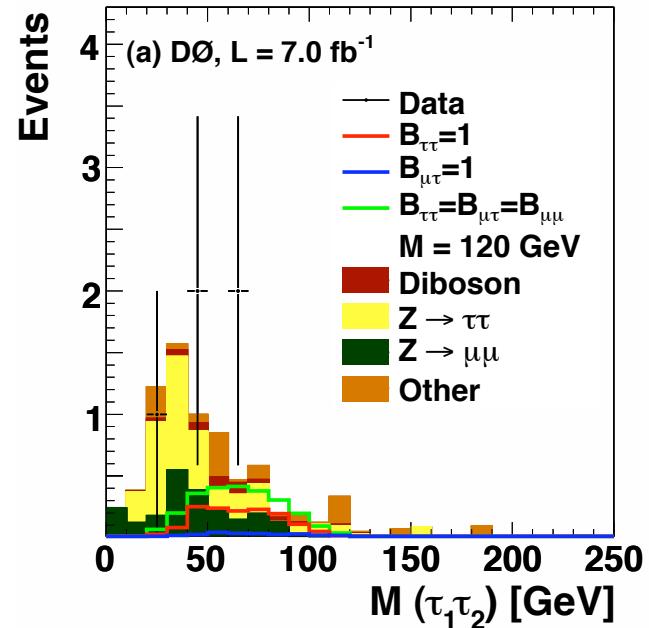
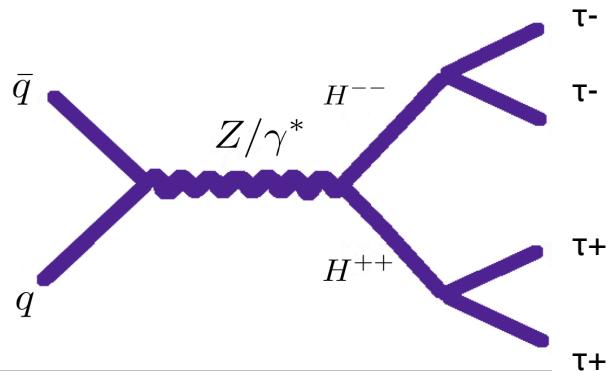


Channels have different background composition  
 Different sensitively to different benchmark points

# Discriminating channels

Separate events into four samples, depending on whether the two tau leptons originate from same or from different Higgs bosons.

- TT channel:  $N_\tau = 2, N_\mu = 1, q(\tau_1) = q(\tau_2)$
  - Sensitive to benchmark points (1) and (5)
  - Main backgrounds  $Z \rightarrow \tau\tau$

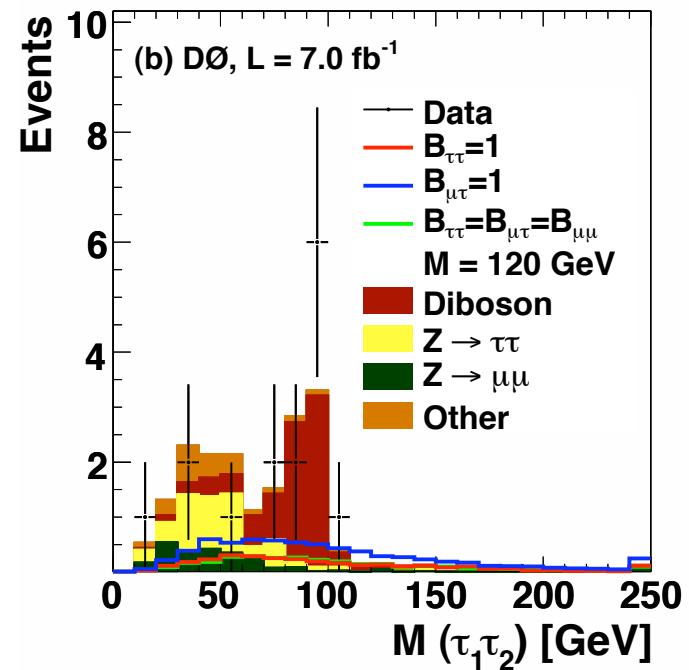
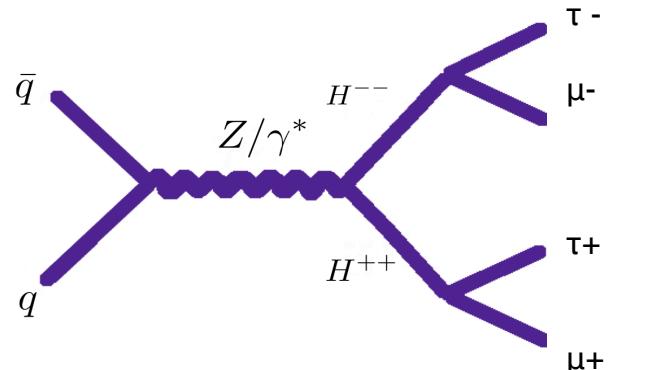


# Discriminating channels

Separate events into four samples, depending on whether the two tau leptons originate from same or from different Higgs bosons.

- TM channel:  $N_\tau = 2, N_\mu = 1, q(\tau_1) \neq q(\tau_2)$

- Sensitive to benchmark point (4)
- Main backgrounds  $Z \rightarrow \tau\tau$ , and di-boson

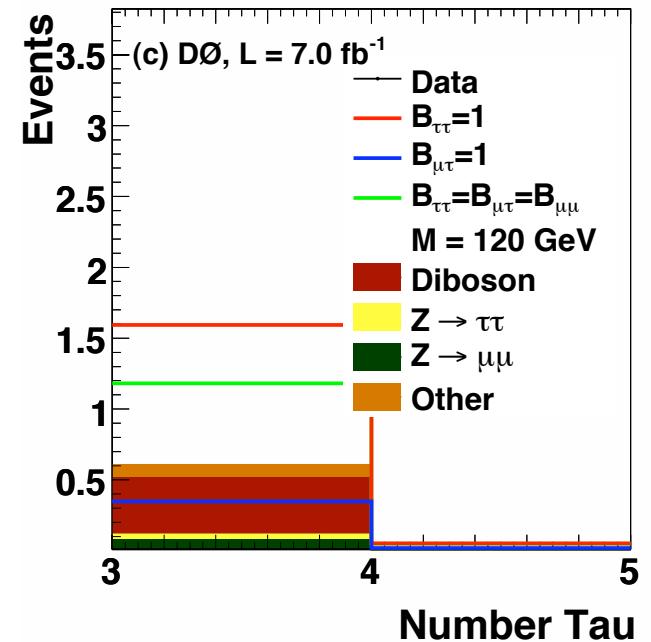
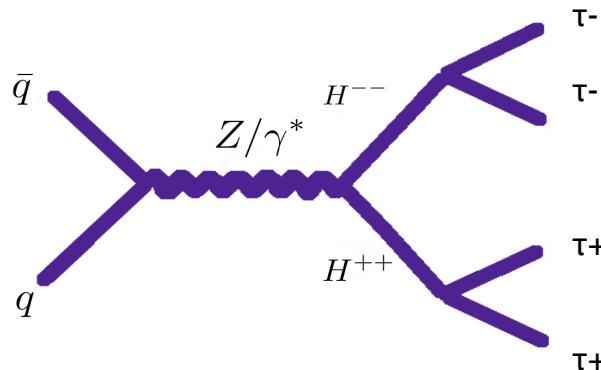


# Discriminating channels

Separate events into four samples, depending on whether the two tau leptons originate from same or from different Higgs bosons.

- T3 Channel:  $N_\tau = 3, N_\mu = 1$

- Sensitive to benchmark points (1) and (5)
- Main backgrounds di-boson

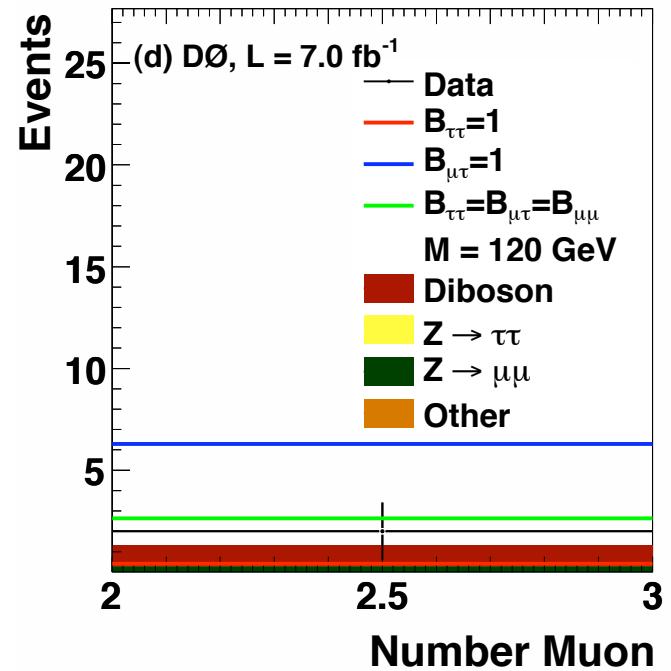
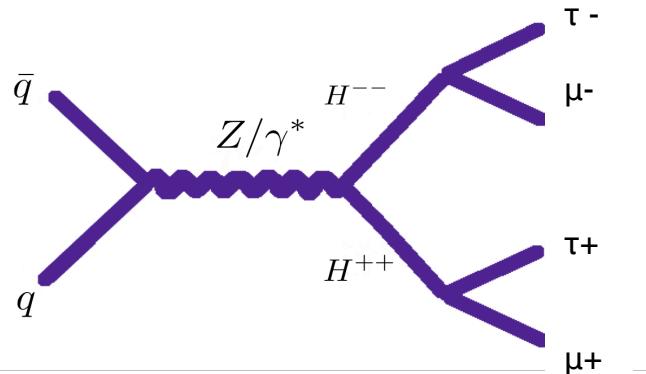


# Discriminating channels

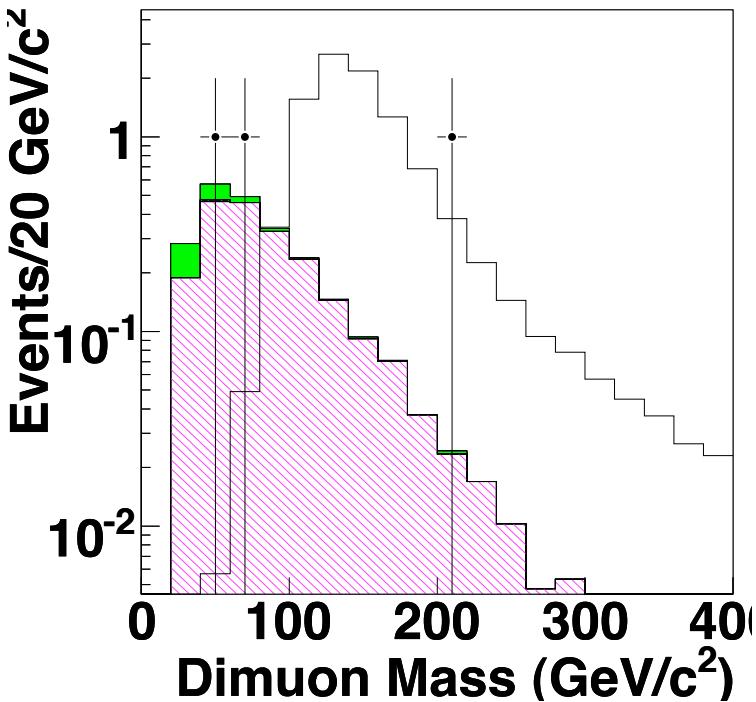
Separate events into four samples, depending on whether the two tau leptons originate from same or from different Higgs bosons.

- M2 Channel:  $N_\tau = 2, N_\mu = 2$

- Sensitive to benchmark point (4)
- Main backgrounds di-boson



# Combination with $B(H^{\pm\pm} \text{ to } \mu\mu) = 1$ analysis



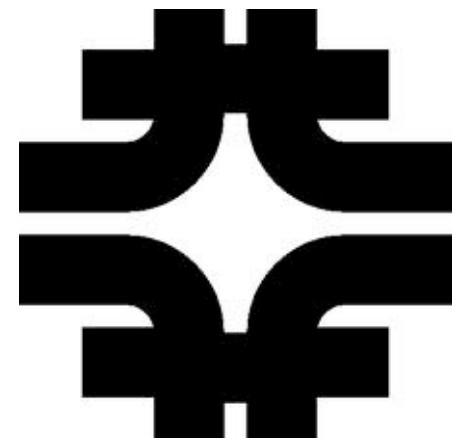
- For benchmark points (2) and (3) need a sample with  $B(H^{\pm\pm} \text{ to } \mu\mu) = 1$
- Combine with previous DØ analysis in this decay channel, with total luminosity  $1.1 \text{ fb}^{-1}$
- Looked for 3 isolated muons
- Final discriminant  $M(\mu\mu)$ , of highest  $p_T$  muons
- 3 candidate events found for  $2.3 \pm 0.5$  expected backgrounds.
- Phys. Rev. Lett. **101**, 071803 (2008)

# Systematic uncertainties

Source of uncertainty	Relative error on each samples [%]					$H^{\pm\pm} \rightarrow 4\mu$	
	$Z/\gamma^*$	$W+\text{jets}$	$t\bar{t}$	Diboson	Signal	Diboson	Signal
Cross section	6.0	6.0	10.0	7.0	–	5.0	–
Luminosity	6.1	6.1	6.1	6.1	6.1	6.1	6.1
Muon Id	2.9	2.9	2.9	2.9	2.9	2.0	6.0
Tau Track match per $\tau$	1.4	1.4	1.4	1.4	1.4	–	–
Tau ID per $\tau$ ( $\tau$ -Type-1/2)	7/4	7/4	7/4	7/4	7/4	–	–
Tau lepton energy scale	1.0	1.0	1.0	1.0	1.0	–	–
Trigger	5.0	5.0	5.0	5.0	5.0	–	–
PDF	–	–	–	–	4.0	–	4.0
Charge misidentification	–	–	–	–	–	20.0	20.0

$B(H^{\pm\pm} \rightarrow \mu\mu) = 1$   
analysis uncertainties

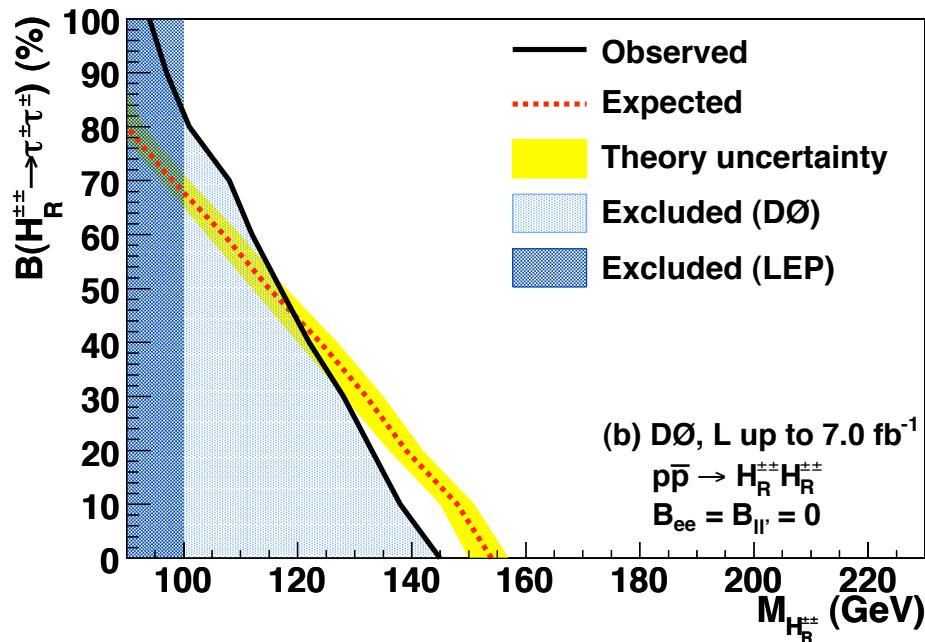
## Cross section limits



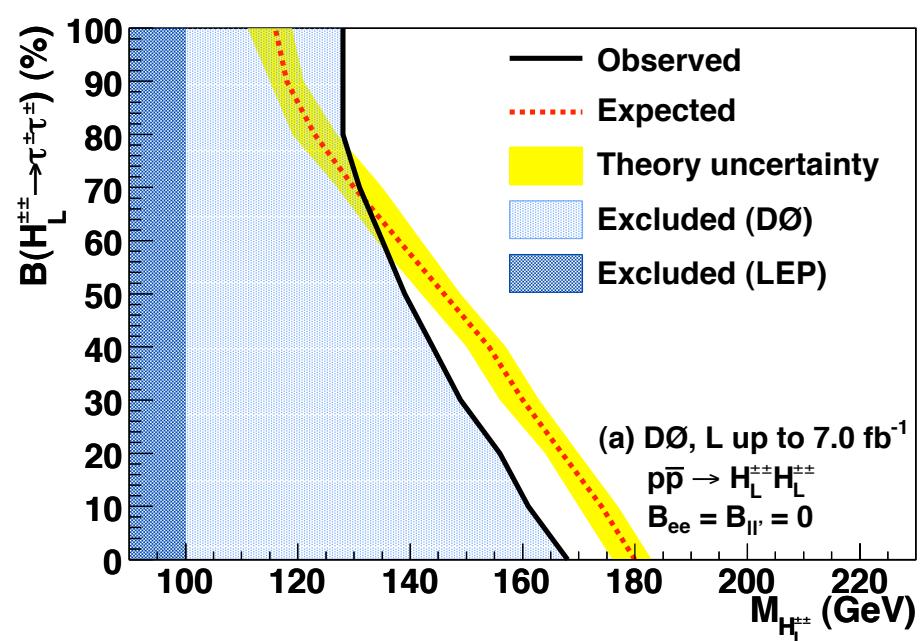
# Mass Exclusions: Benchmarks 1 - 3

$$B(H^{\pm\pm} \rightarrow \tau\tau) + B(H^{\pm\pm} \rightarrow \mu\mu) = 1$$

Right Handed  $H^{\pm\pm}$



Left Handed  $H^{\pm\pm}$

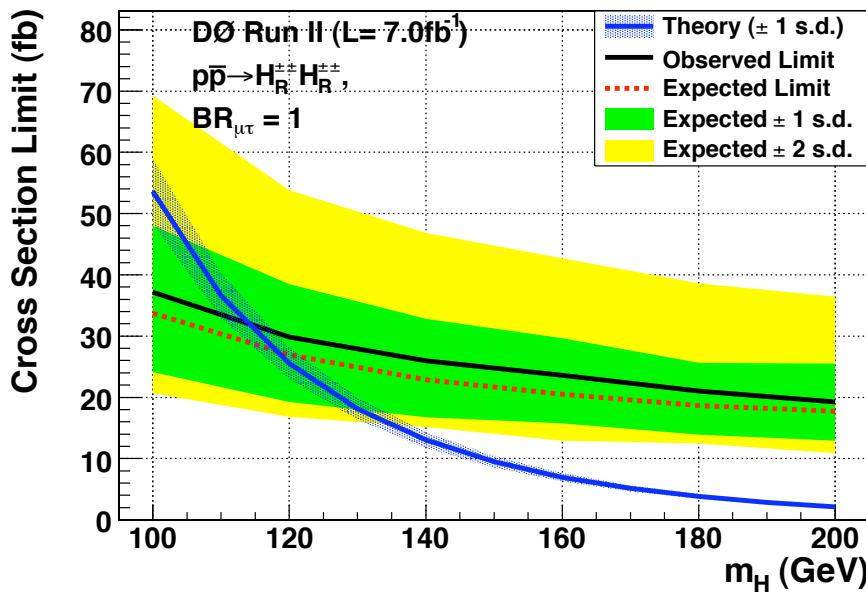


Set at 95% Confidence Level, using the CLs method

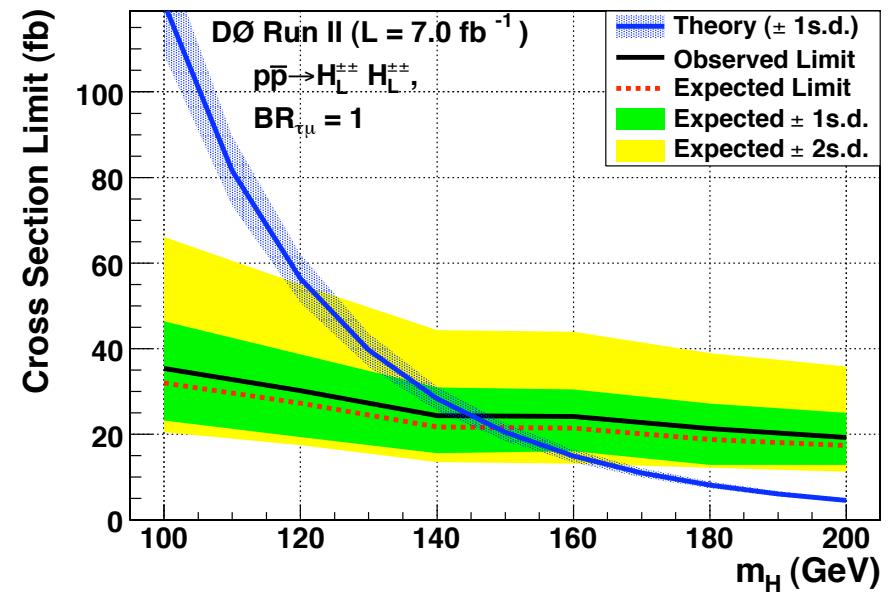
# Limits: Benchmark point 4

$$B(H^{\pm\pm} \rightarrow \mu\tau) = 1$$

Right Handed



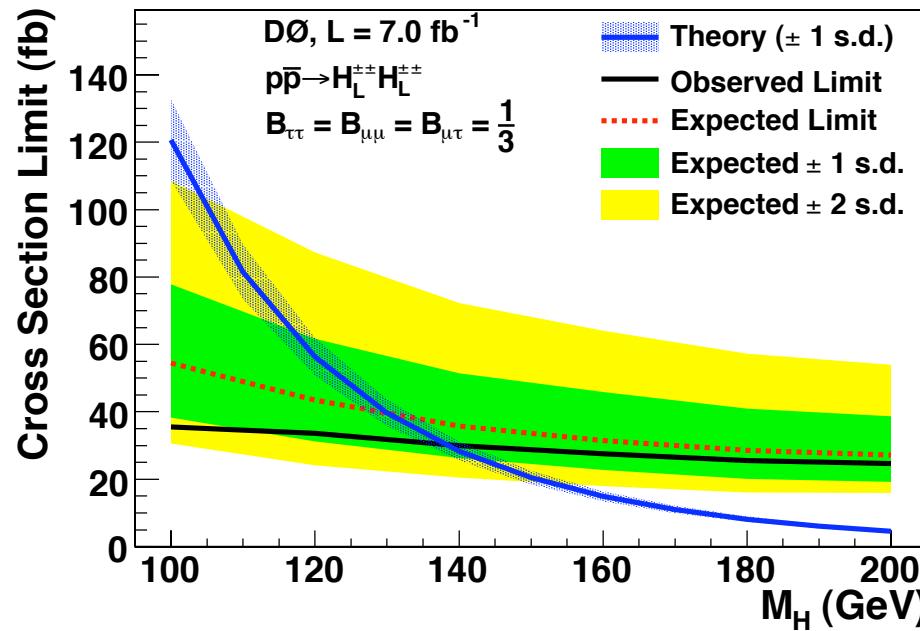
Left Handed



Set at 95% Confidence Level, using the CLs method

# Limits: Benchmark 5

$$B(H^{\pm\pm} \rightarrow \tau\tau) = B(H^{\pm\pm} \rightarrow \mu\mu) = B(H^{\pm\pm} \rightarrow \mu\tau) = \frac{1}{3}$$

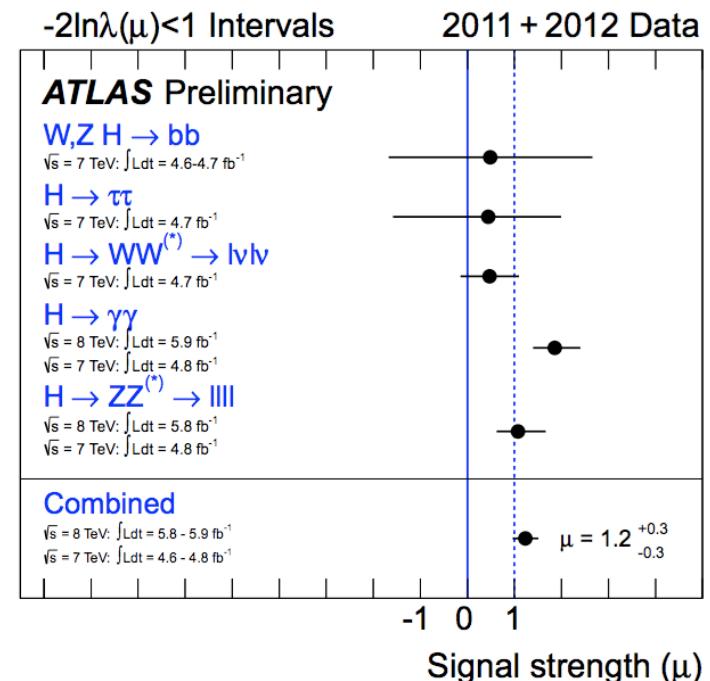
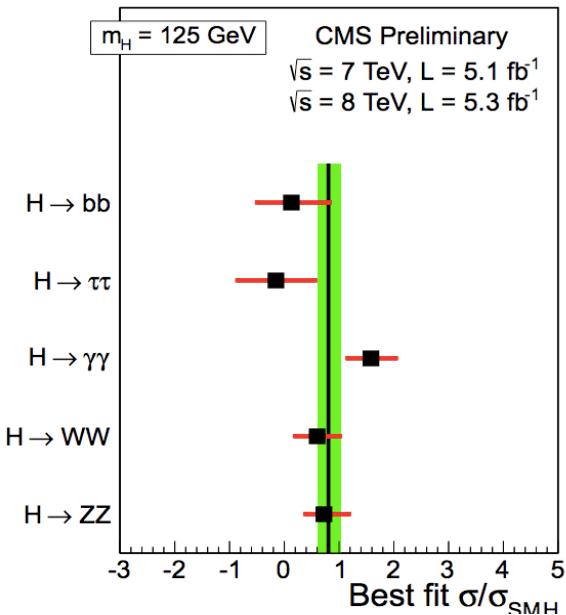


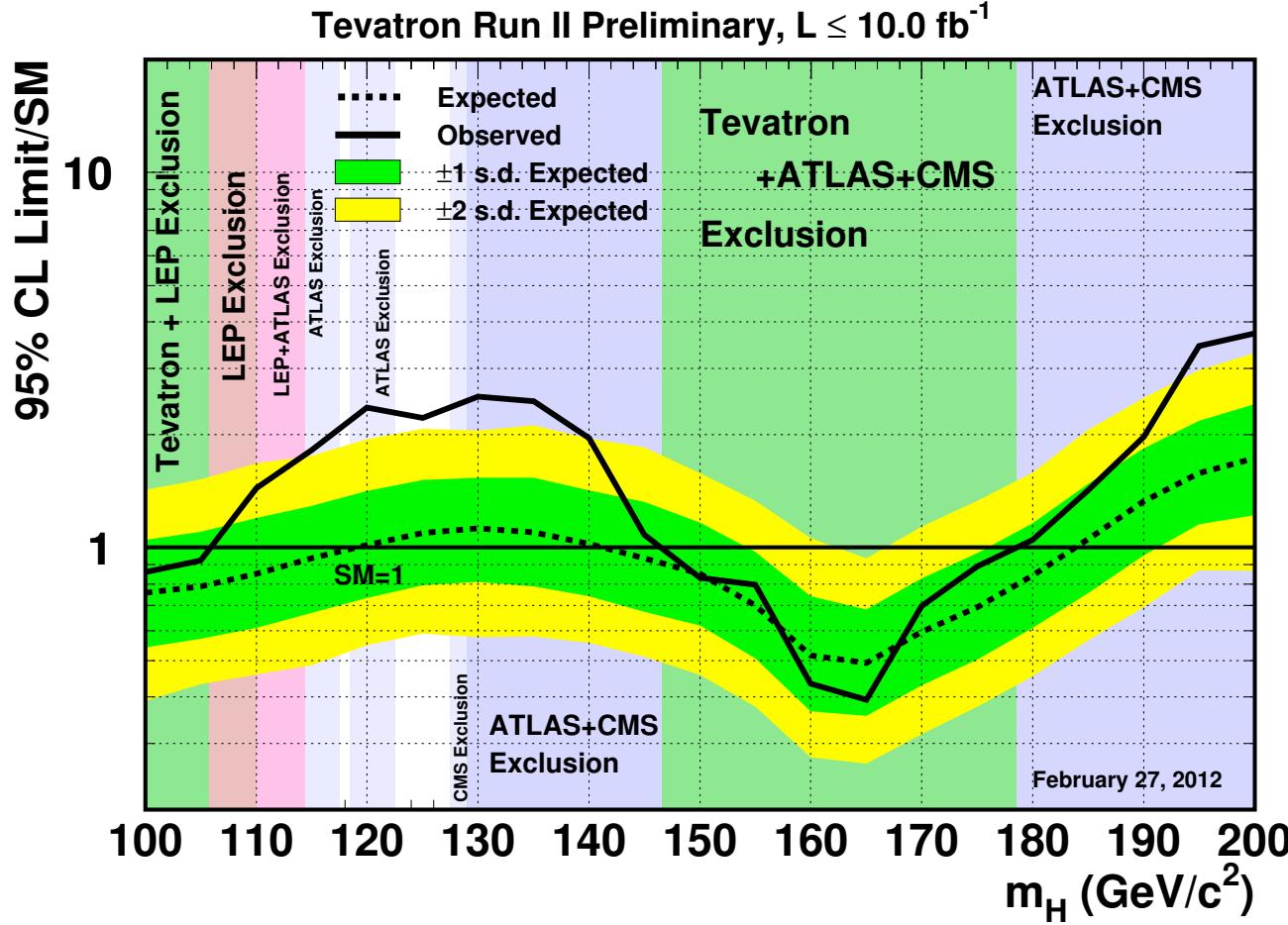
Benchmark point specific to Little Higgs models for which there is no right handed  $H^{\pm\pm}$

# A search for the SM Higgs boson at DØ

# LHC SM Higgs results

- Results from LHC on the observation of a new particle consistent with the SM Higgs boson of  $M_H \approx 125$  GeV
- Dominant channels  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ$
- All channels consistent with the SM
- Only channels with sensitivity to claim observation are boson decay
- No evidence seen in fermionic decay channels



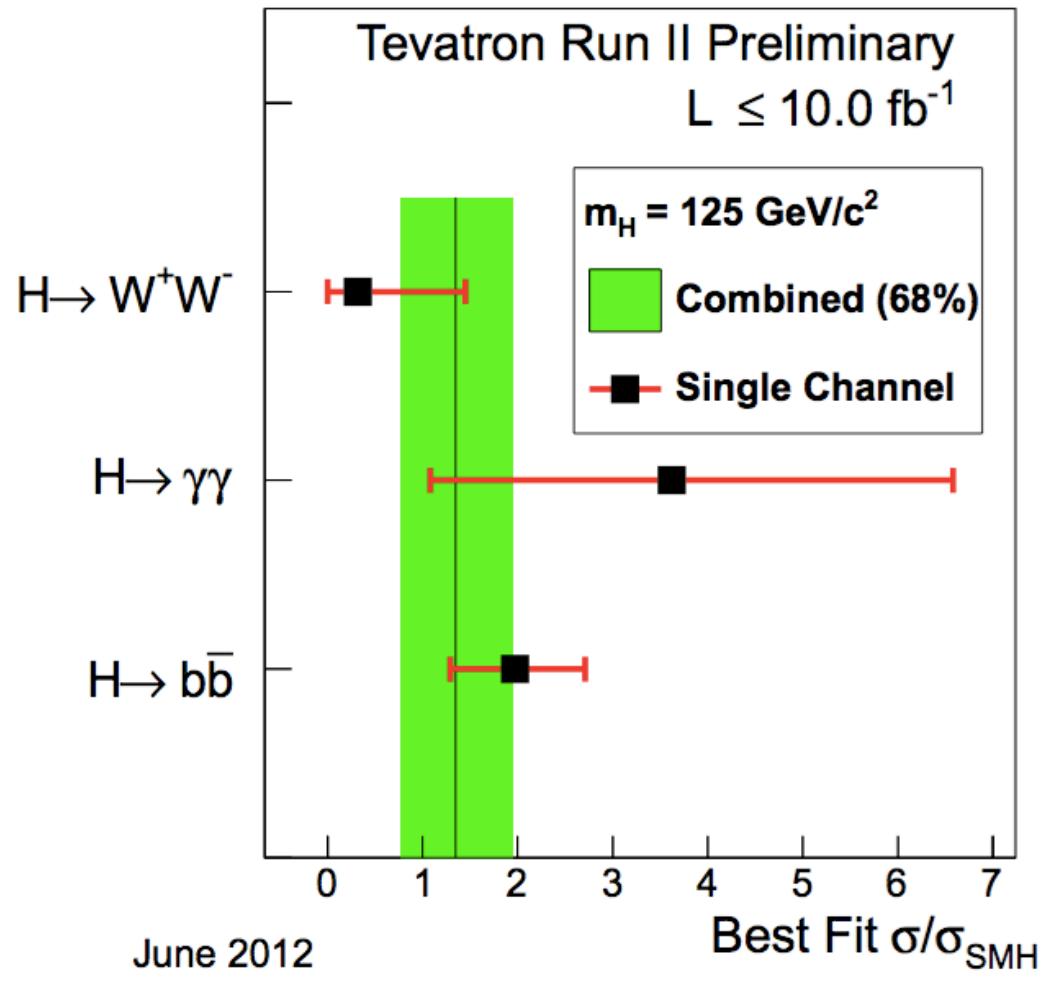


## Combined DØ and CDF results

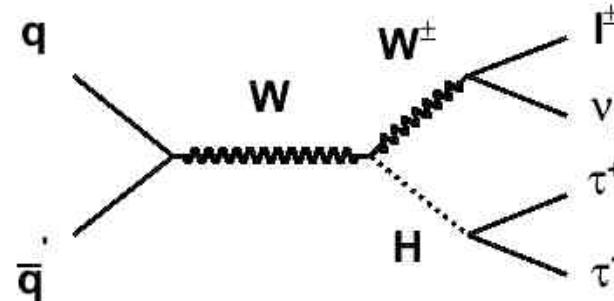
- The most sensitive channels are  $H \rightarrow bb$  and  $H \rightarrow WW$
- Exclude masses 100-106 GeV and 147-179 GeV
- A SM Higgs boson-like excess is seen for  $115 < M_H < 135$  GeV, with a local significance of  $3.0\sigma$  and global significance of  $2.5\sigma$

# Tevatron comparison to SM Higgs cross section

- All Tevatron results are consistent with a SM Higgs
- Evidence seen only in  $H \rightarrow b\bar{b}$  channel
- For 125 GeV Higgs the dominant leptonic Higgs decays are to  $\tau\tau$  pairs
- No evidence seen in leptonic channels



# $\tau\tau\mu + X$ analysis

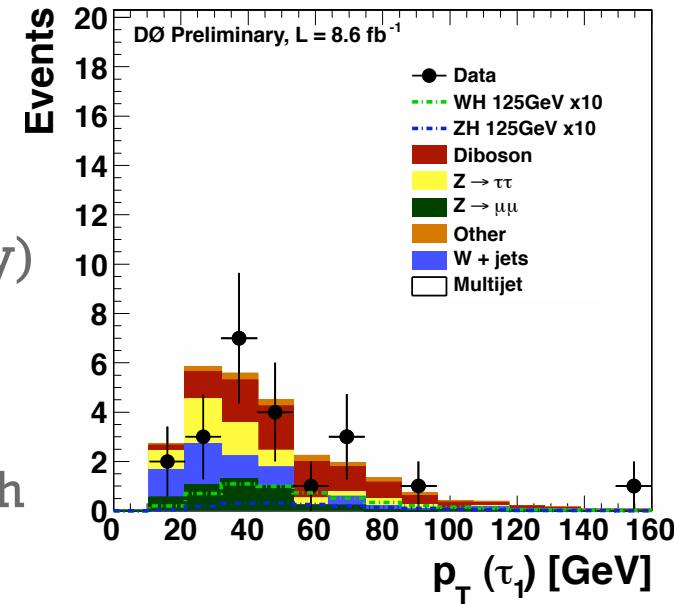


- Search for two hadronically decaying taus assumed to originate from Higgs, with a muon from a W or Z boson decay.
- To reduce background from jets, taus are searched for with additional leptons.
- This decay channel has not been studied at DØ previously.
- CDF studied the channel  $\tau\tau l$  where  $l = \mu, e$  and determined expected (observed) cross section limits of 57.3 (46.2) for  $M_H = 125$  GeV, for  $L = 6.2 \text{ fb}^{-1}$ .

# Event selection

Build on H<sup>±±</sup> framework, using an integrated luminosity L = 8.6 fb<sup>-1</sup>

- $M_T > 20 \text{ GeV}$  (transverse mass)
  - $\text{MET} > 20 \text{ GeV}$  (missing transverse energy)
  - $|Q| = |q_1 + q_2 + q_3| = 1$
  - $\Delta R(\mu\tau) > 0.5$  for the two selected taus with the selected muon
  - $NN > 0.75/0.75/0.95$  for tau lepton Type-1/Type-2/Type-3
  - Tri-lepton veto: remove events that overlap with the other DØ tri-lepton analysis.

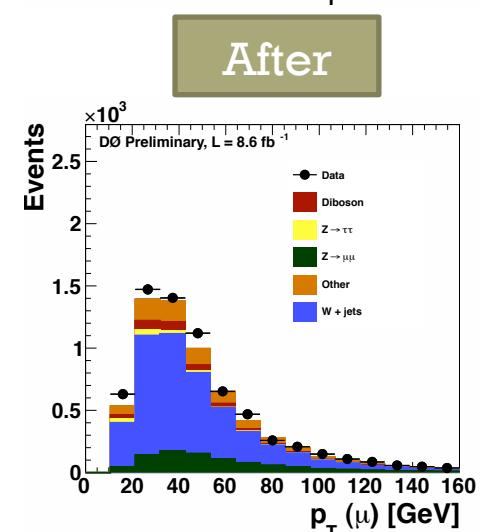
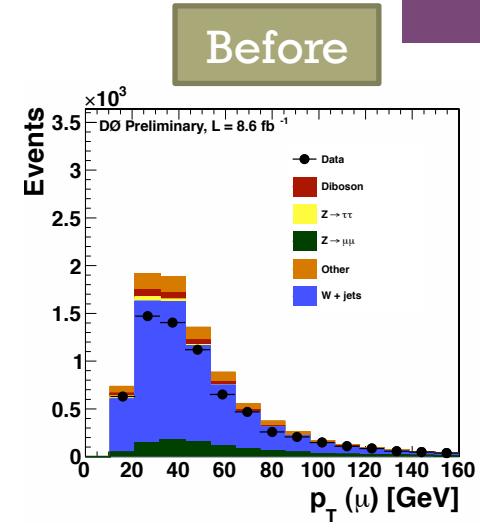


# W+jets background

jets can be mis-identified as hadronic tau decays

- Rate of W+jets events not well modeled by MC.
- Reweight W+jet MC events to data in W boson enriched region.
- Reweighting determined per tau type and for same-sign (SS) and opposite-sign (OS) tau-tau combinations.

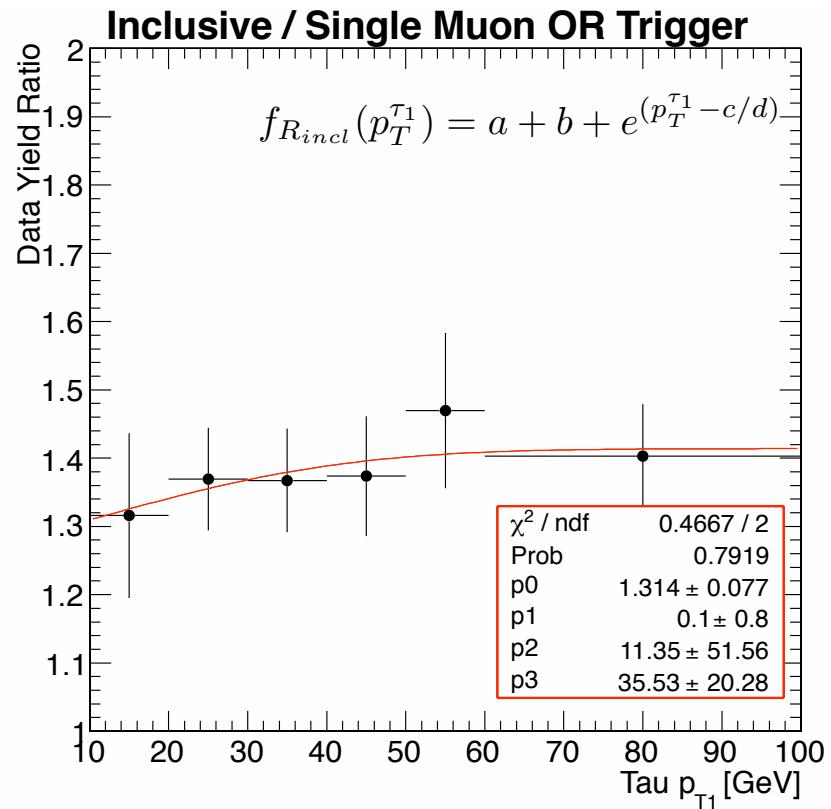
Tau lepton Type	$R_W$ value	
	OS	SS
Type-1	$0.82 \pm 0.02$	$1.14 \pm 0.03$
Type-2	$0.63 \pm 0.02$	$1.12 \pm 0.03$
Type-3	$0.52 \pm 0.02$	$0.55 \pm 0.02$

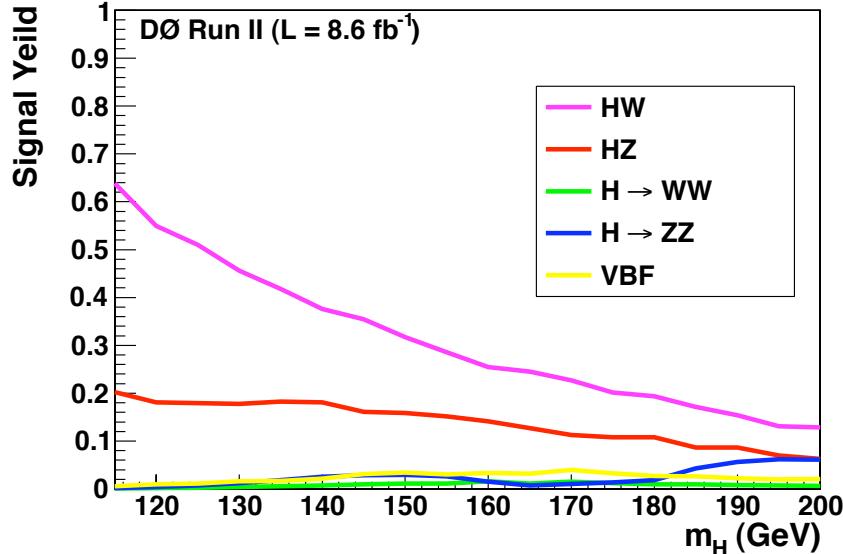


# Inclusive Trigger

## Data driven method

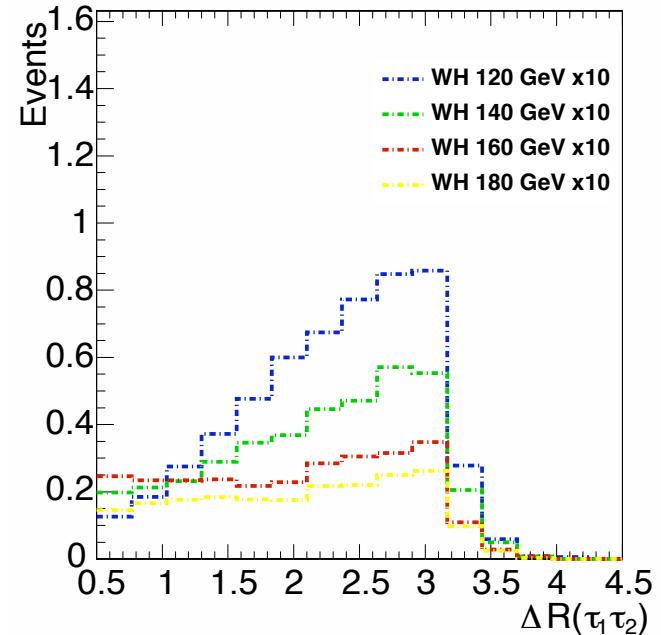
- Method derived to increase statistics.
- All events that pass selection criteria can be used regardless of whether they passed a specific trigger.
- Efficiency of this “inclusive” trigger derived as a function of  $p_T$  of leading tau lepton.
- Derived as a additional correction with respect to single muon triggers.





## Signal Sensitivity

- Analysis most sensitive to associated production modes
- Sensitive to  $H \rightarrow \tau\tau$  at  $M_H < 130 \text{ GeV}$  and  $H \rightarrow WW$  above

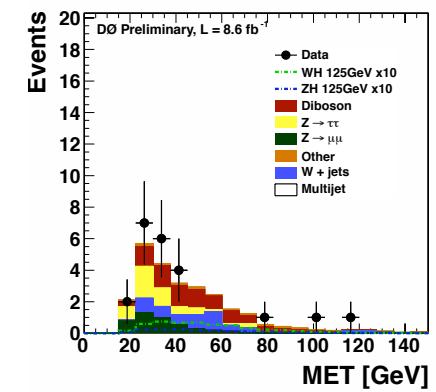
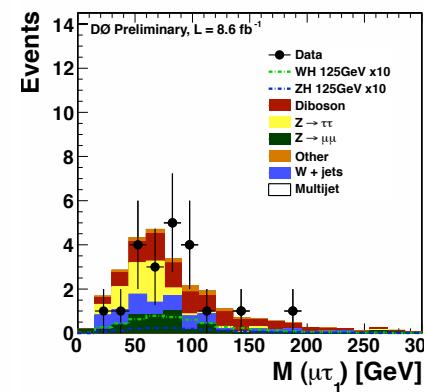
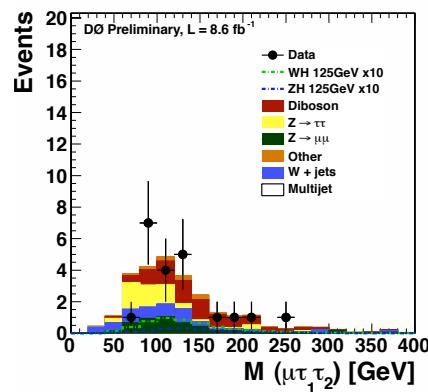
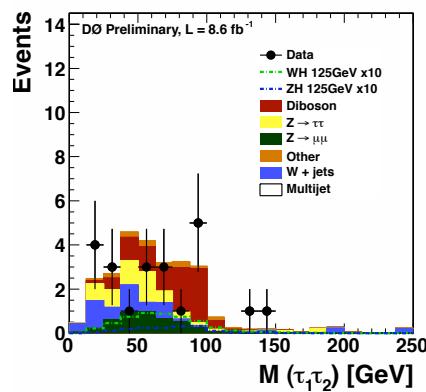
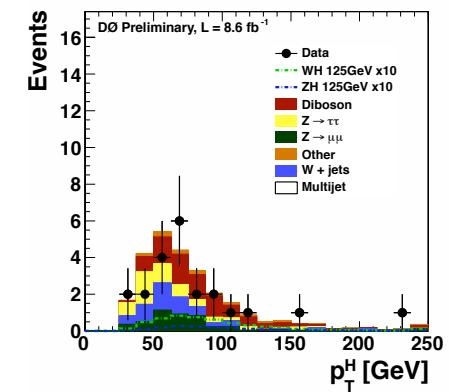
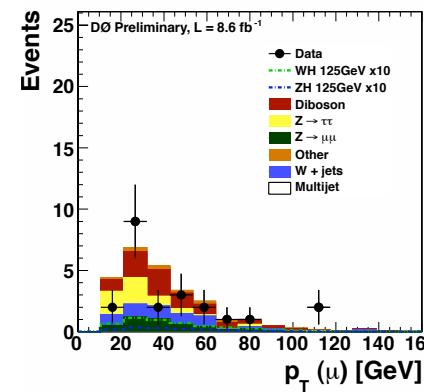
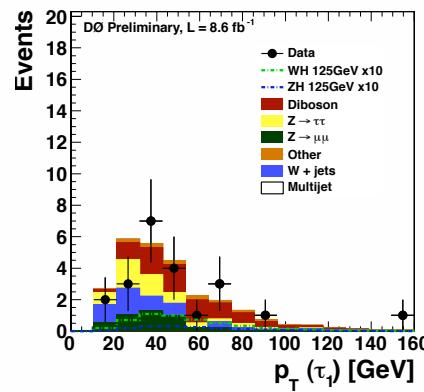
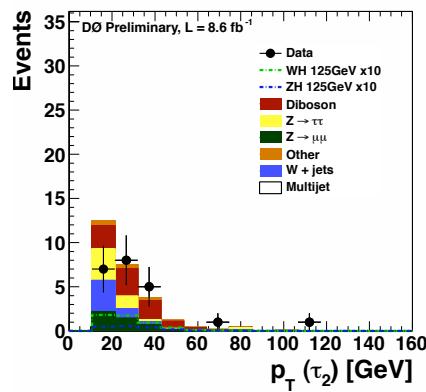
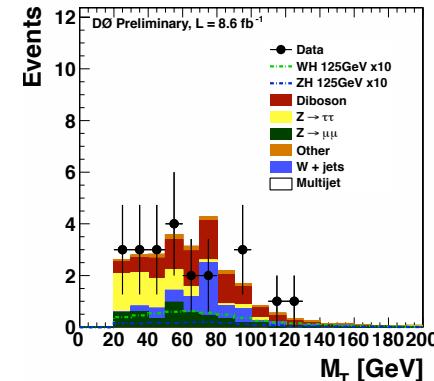


# Multivariate analysis methods

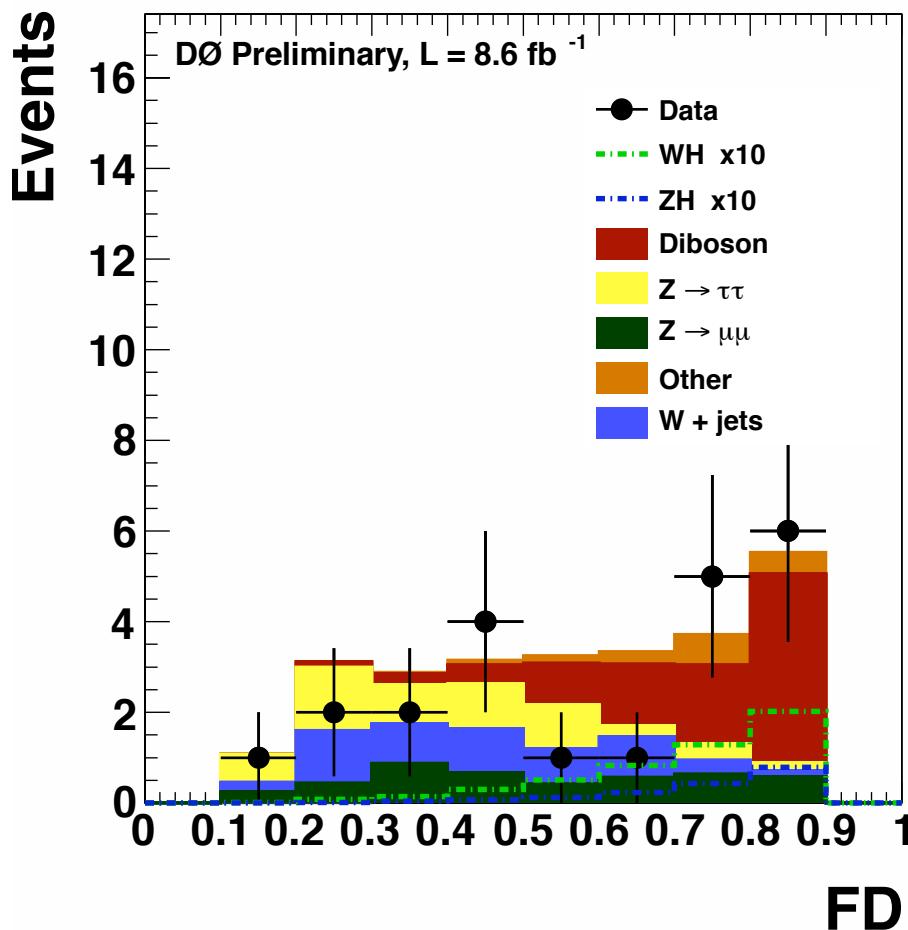
- Two stage BDT implemented.
- BDT pass 1 – trained against all backgrounds samples except di-bosons.
- Create a high purity di-boson sample by cutting on output of BDT pass 1.
  - The di-boson background most similar in shape to signal.
- BDT pass 2 – trained on all background samples that pass the requirement on the first BDT.

# Discriminating Variables for BDT pass 1

9 input variable used to train BDT pass 1



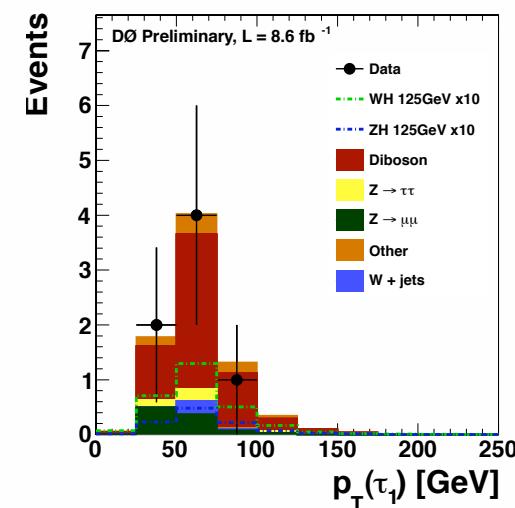
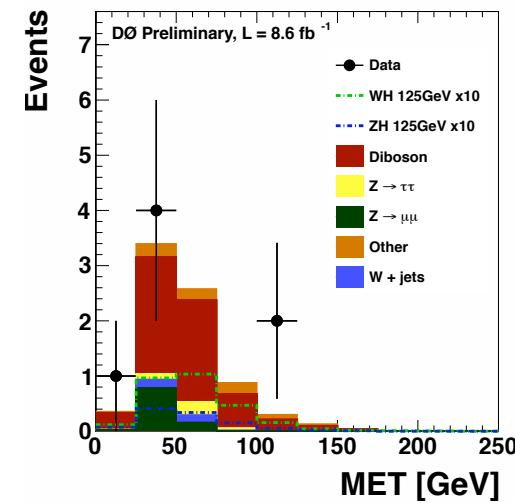
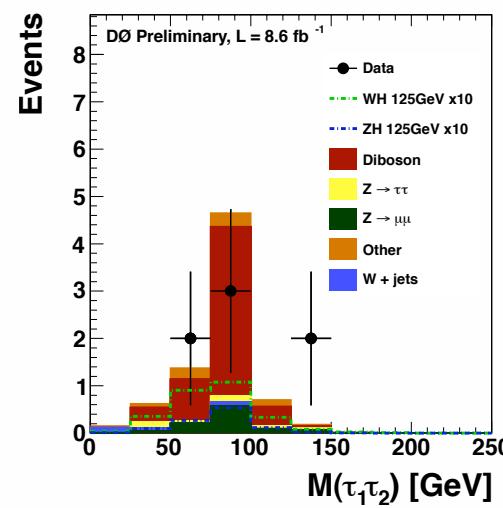
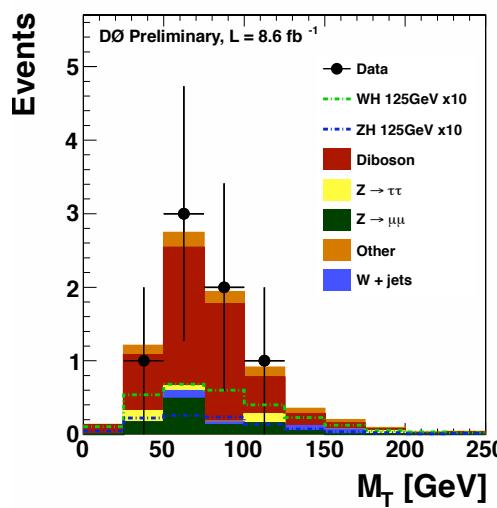
# BDT Pass 1 output for $M_H = 125 \text{ GeV}$



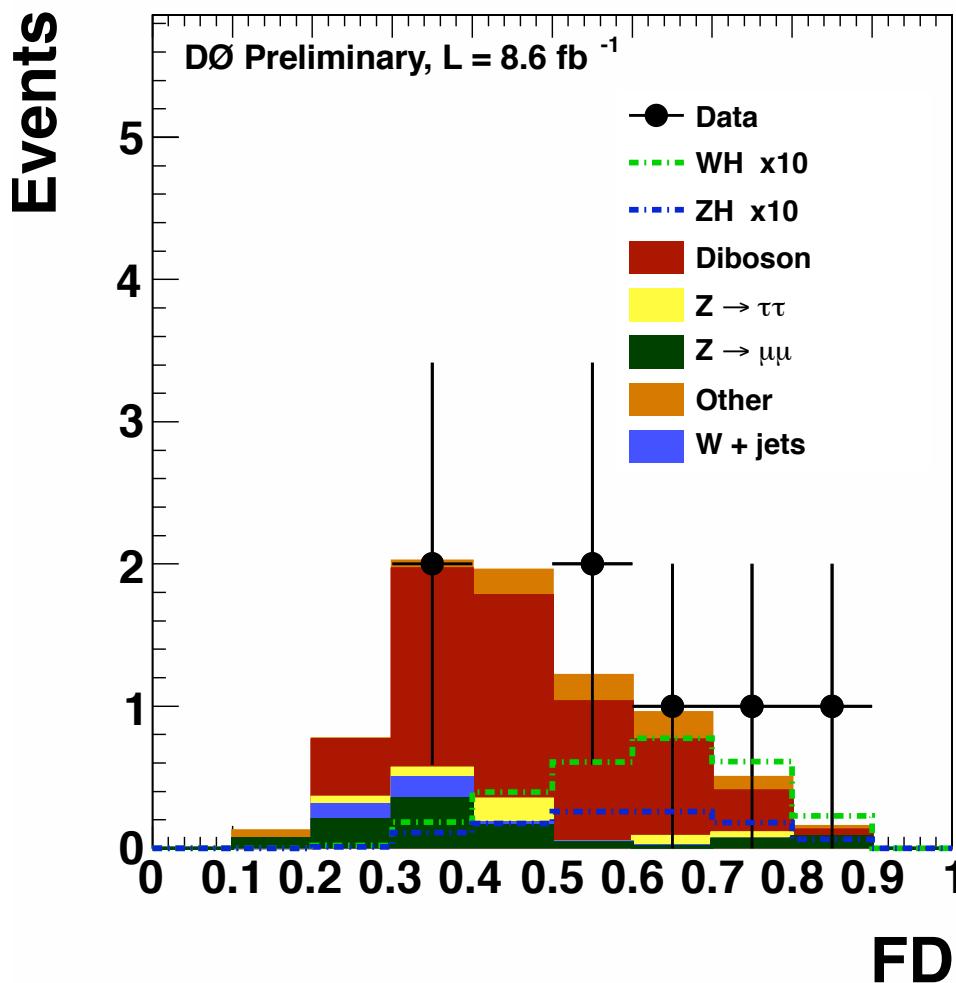
- Signal and di-boson events peak at high values and other backgrounds at low values.
- Determine optimized background rejection.
- Apply Higgs mass specific requirement on this variable.
- Events that pass used to train BDT pass 2.

# Discriminating variables for BDT pass 2

- After selection requirement number of signal and background is now mass dependent.
- Distributions shown for  $M_H = 125 \text{ GeV}$



# BDT Pass 2 output for $M_H = 125 \text{ GeV}$



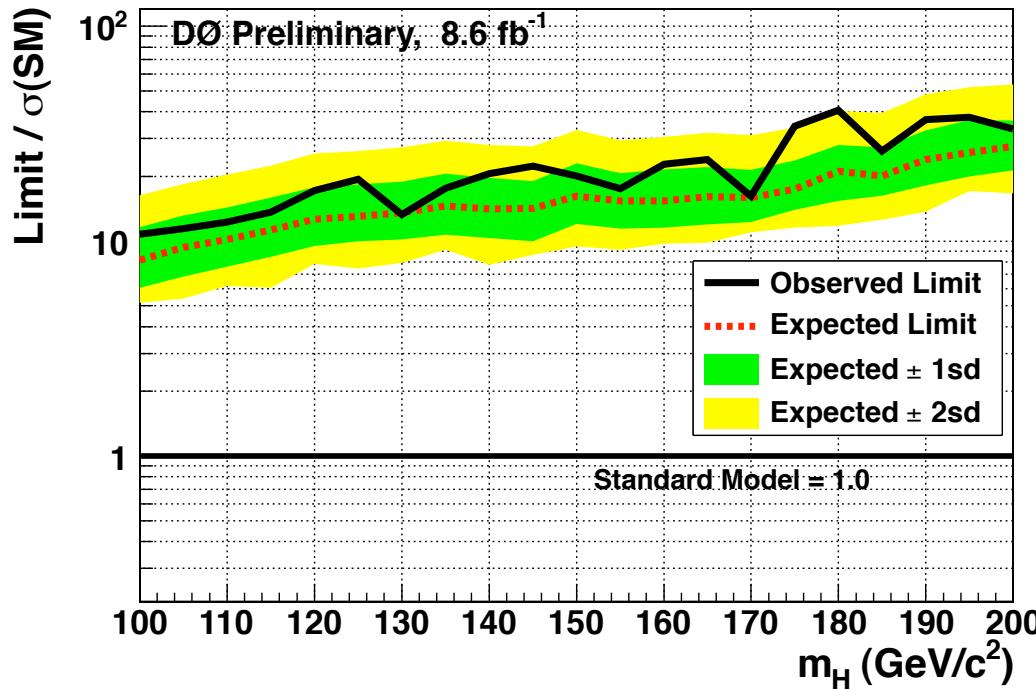
- After requirement on BDT pass 1, sample dominated by di-boson backgrounds
- Signal events peak towards high values and background towards low values
- Used as discriminant variable for limit setting

# Systematic uncertainties

Only normalisation uncertainties, apart from inclusive trigger uncertainty which is differential (shape dependent).

Contribution	Diboson	Backgrounds			Signals		
		$Z/\gamma^*$	$t\bar{t}$	$W+\text{jet}$	$ggH$	$\text{VBF}$	$VH$
Luminosity	6.1	6.1	6.1	6.1	6.1	6.1	6.1
SingleMuonOR trigger	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Inclusive trigger	s	s	s	s	s	s	s
Cross section	7.0	6.0	10.0	6.0	7.6	4.9	6.2
$\tau$ lepton Id	6.9	6.9	6.9	6.9	6.9	6.9	6.9
$W+\text{jet}$ reweighting	–	–	–	3.0	–	–	–
Muon Id	1.8	1.8	1.8	1.8	1.8	1.8	1.8

# Cross section limits



Both BDT pass 2 and the region of BDT pass 1 that fail the background rejection requirement are combined to set cross section limits as ratio to SM Higgs cross section

# Conclusion

- Two analyses have been presented a search for a doubly charged Higgs and search for the SM Higgs
- Doubly charged Higgs analysis
  - Set limits for 5 benchmark points
  - Points (1), (2), (5) had not been searched for before
  - Set world's best limits for all points
  - Published in Phys. Rev. Lett. **108** 021801 (2012)
- $H^{\pm\pm}$  limits have been superseded by results by LHC
  - CMS studied all lepton pair combinations, setting limits between  $M(H^{\pm\pm}) > 165$  to 457 GeV for left handed Higgs bosons.
  - ATLAS studied muon decays and set limits  $M(H^{\pm\pm}) > 355$  GeV for left handed states and  $M(H^{\pm\pm}) > 251$  GeV for right handed states.

# Conclusion

- SM Higgs search
  - First time this channel has been searched for at DØ
  - Conference note – D0 Note 6286-CONF
  - In process of being published, together with DØ analyses sensitive to associated production of Higgs boson where the Higgs decays leptonically.
  - Results from this channel included in the DØ and Tevatron combinations.

# Backup

# Cross section limits

- Set at 95% Confidence Level, using the CLs method.

$$CL_S = \frac{CL_{S+B}}{CL_B}$$

- Collie program uses negative-log-likelihood as test statistic

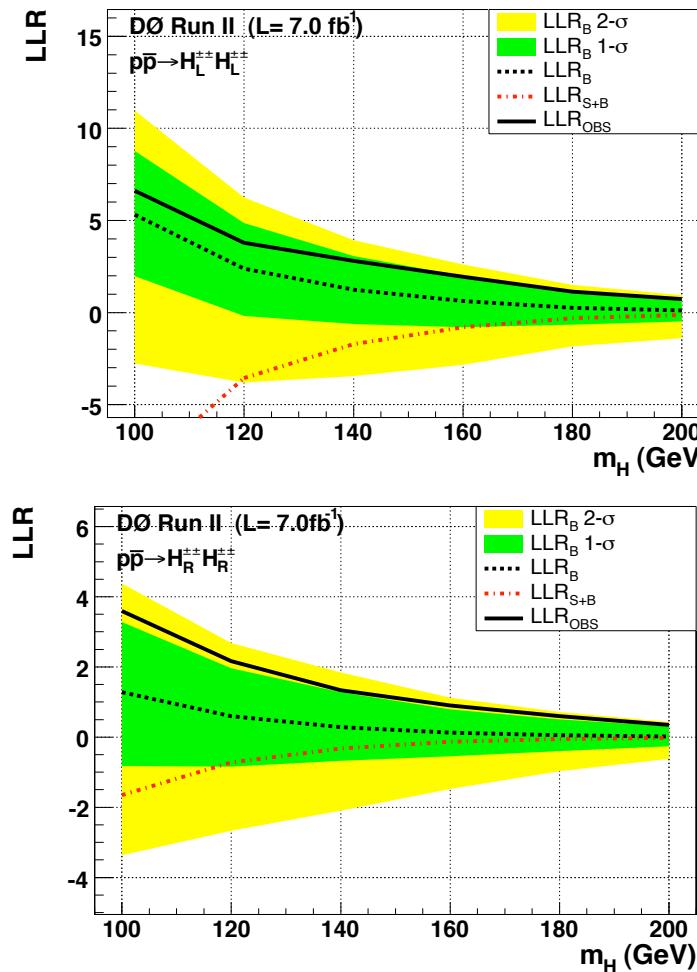
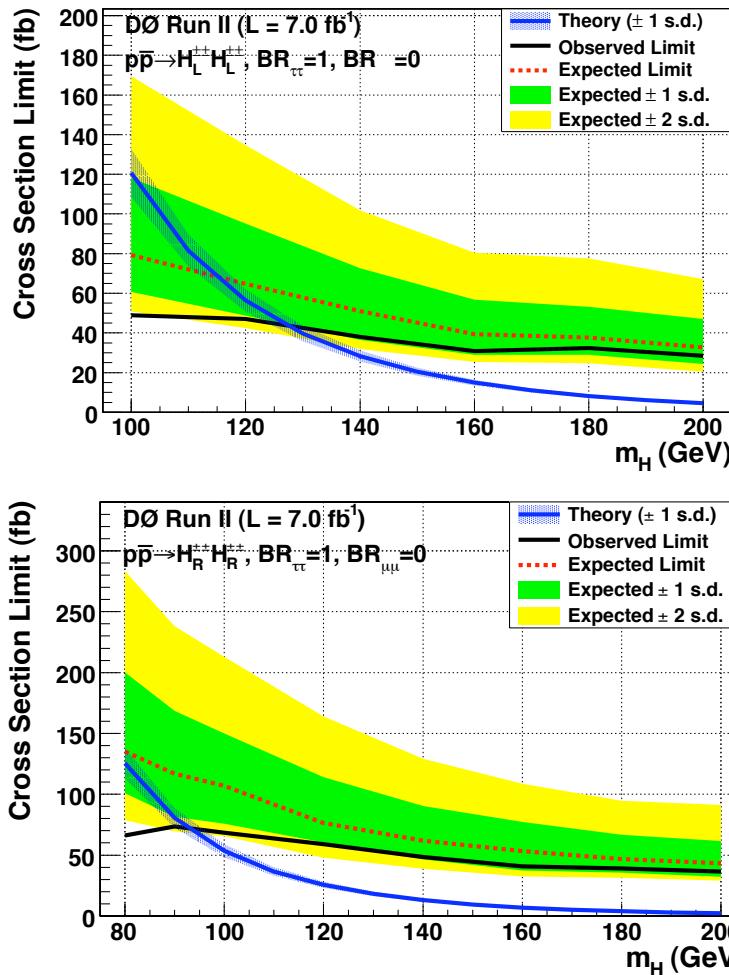
$$LLR(s, b, d) = \sum_{i=0}^{N_{Channels}} \sum_{j=0}^{N_{bins}} s_{ij} - d_{ij} \ln \left( 1 + \frac{s_{ij}}{b_{ij}} \right)$$

# H<sup>±±</sup> event yields

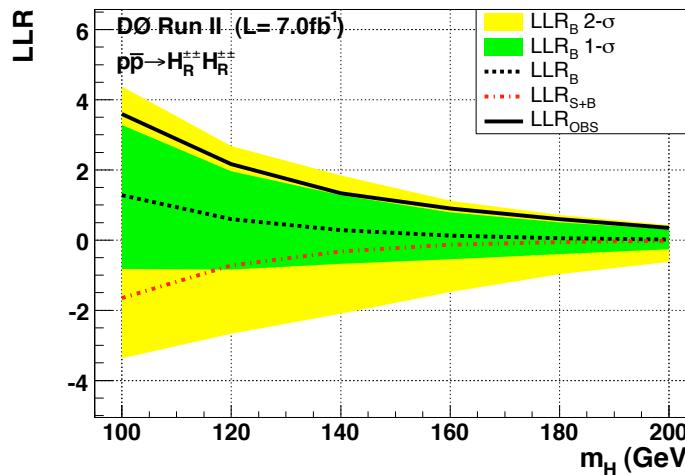
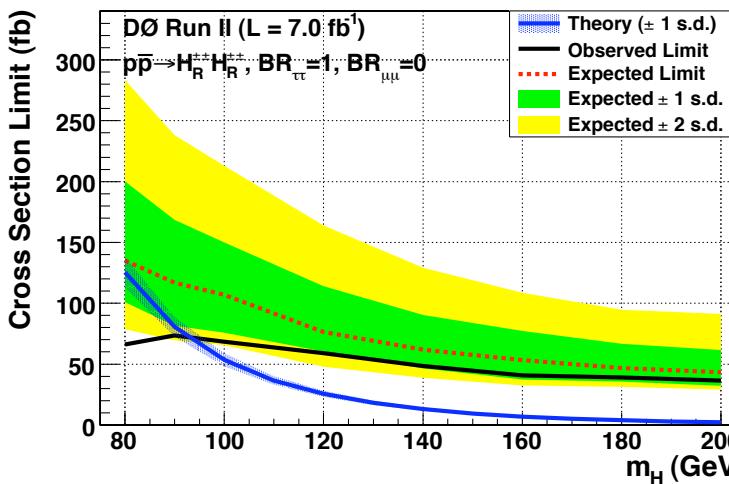
	TT	TM	T3	M2
<b>Data</b>	5	15	0	2
$Z/\gamma^* \rightarrow \tau\tau$	$3.37 \pm 0.47$	$4.75 \pm 0.67$	$0.04 \pm 0.00$	$< 0.01$
$Z/\gamma^* \rightarrow \mu\mu$	$2.24 \pm 0.31$	$2.54 \pm 0.36$	$0.08 \pm 0.01$	$0.2 \pm 0.03$
$Z/\gamma^* \rightarrow \mu\mu$	$< 0.01$	$0.28 \pm 0.04$	$0.01 \pm 0.00$	$< 0.01$
$W + \text{jets}$	$1.08 \pm 0.15$	$1.81 \pm 0.28$	$< 0.01$	$< 0.01$
$t\bar{t}$	$0.27 \pm 0.04$	$0.28 \pm 0.05$	$0.08 \pm 0.01$	$< 0.01$
Diboson	$0.49 \pm 0.08$	$8.50 \pm 1.40$	$0.40 \pm 0.07$	$1.06 \pm 0.17$
Multijet	$0.00 \pm 0.17$	$0.00 \pm 0.52$	$0.00 \pm 0.03$	$0.00 \pm 0.07$
<b>Total Bkg</b>	$7.47 \pm 1.22$	$18.17 \pm 3.32$	$0.61 \pm 0.12$	$1.28 \pm 0.27$
<b>Signal 120 GeV</b>				
$B_{\tau\tau} = 1$	$1.44 \pm 0.20$	$3.08 \pm 0.42$	$1.64 \pm 0.24$	$0.40 \pm 0.05$
$B_{\tau\tau} = B_{\mu\mu} = B_{\mu\tau} = 1/3$	$2.48 \pm 0.34$	$3.12 \pm 0.42$	$1.23 \pm 0.17$	$2.63 \pm 0.40$
$B_{\mu\tau} = 1$	$0.28 \pm 0.04$	$6.83 \pm 0.93$	$0.37 \pm 0.06$	$6.28 \pm 0.86$

# $H^{\pm\pm}$ limits: Benchmark point 1

$$B(H^{\pm\pm} \rightarrow \tau\tau) = 1$$



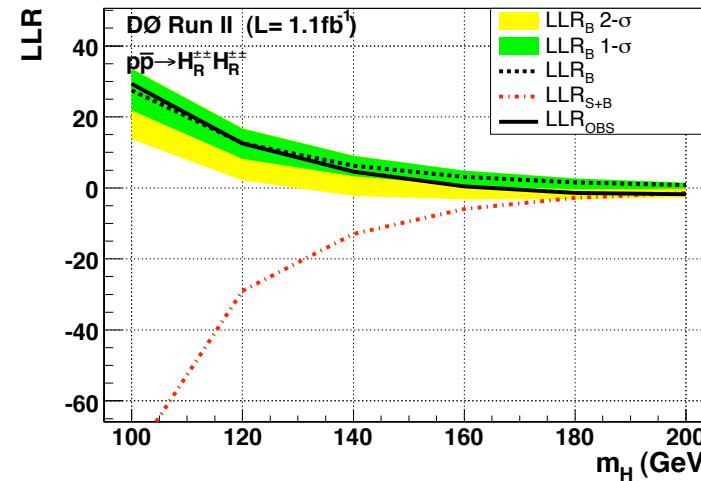
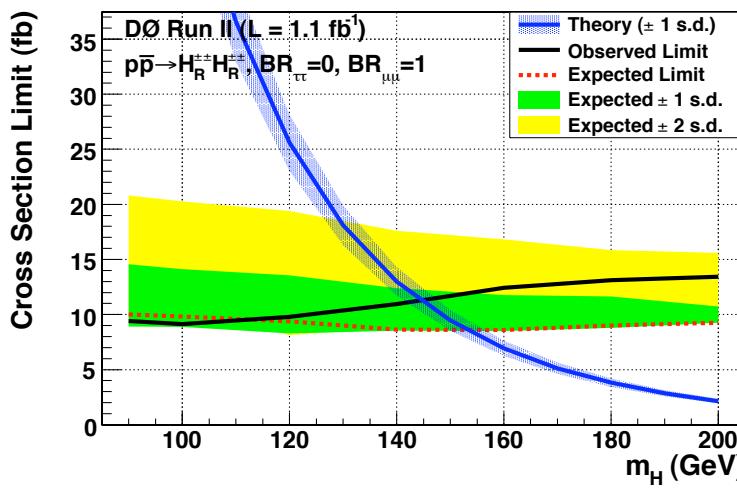
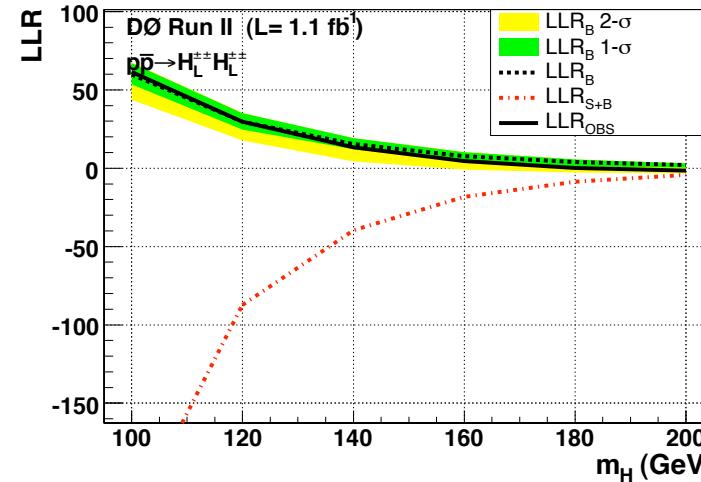
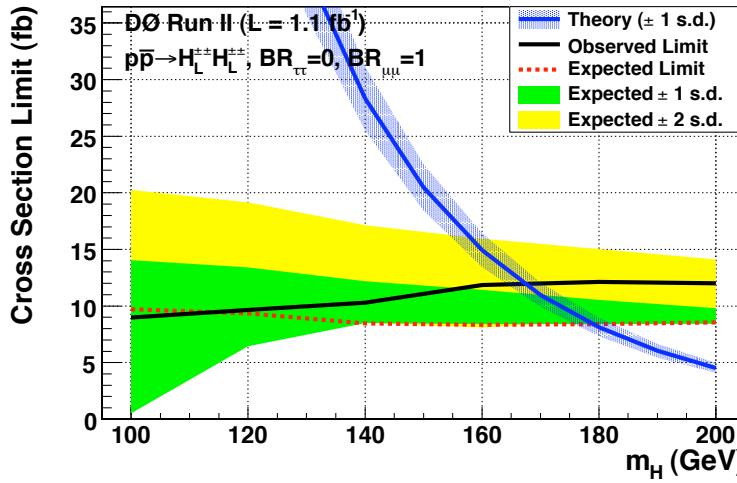
Left  
Handed



Right  
Handed

# $H^{\pm\pm}$ limits: Benchmark point 3

$$B(H^{\pm\pm} \rightarrow \mu\mu) = 1$$

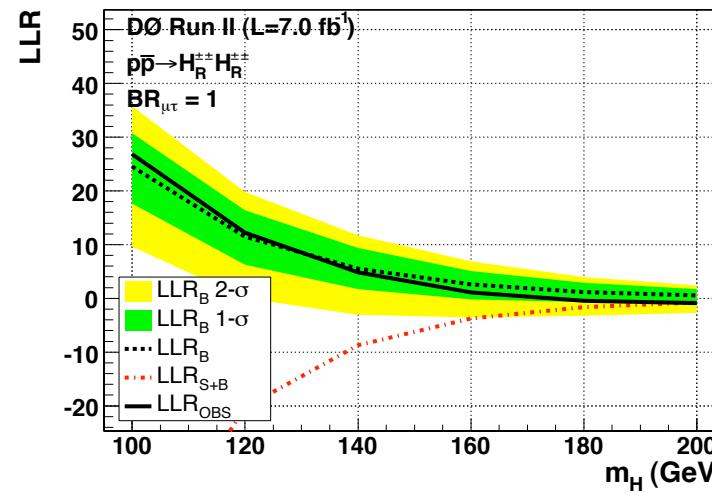
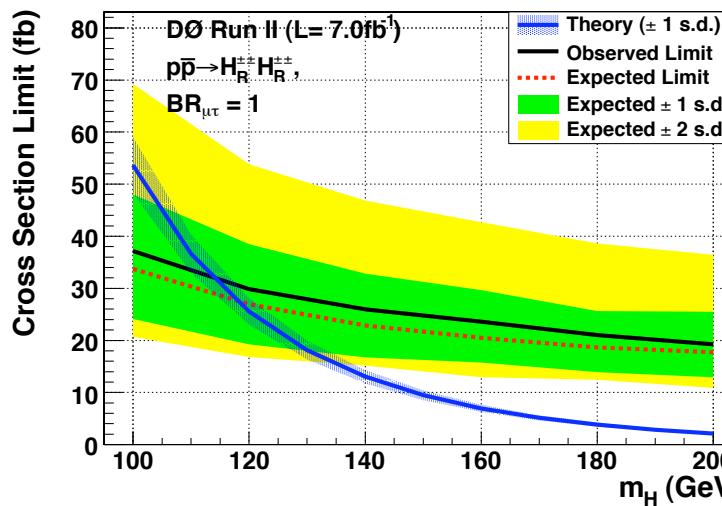
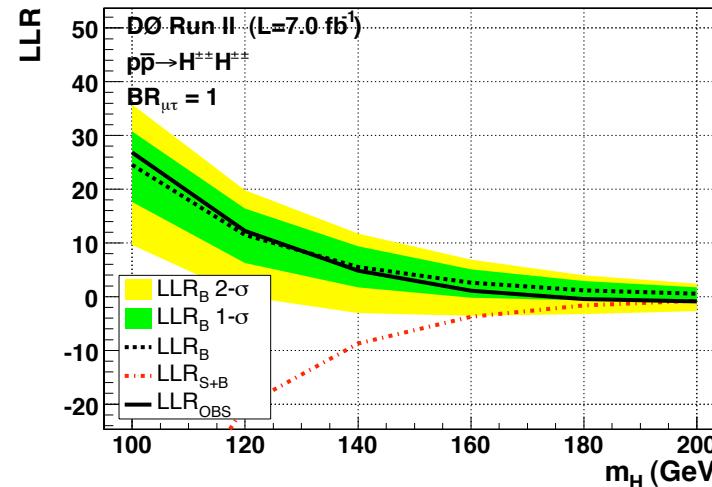
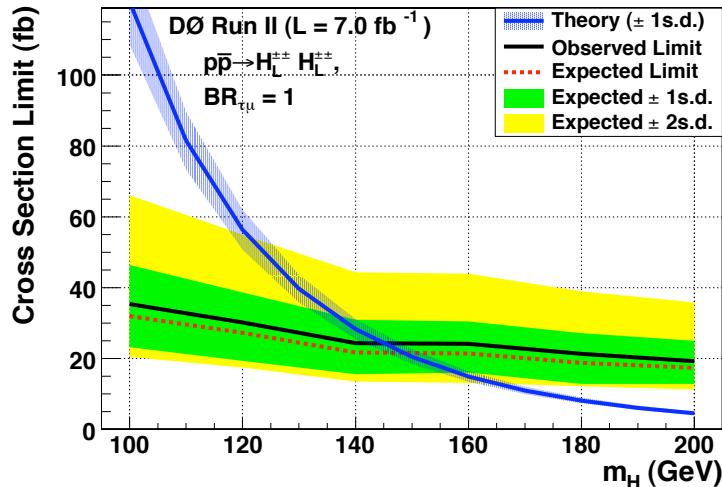


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# $H^{\pm\pm}$ limits: Benchmark point 4

$$B(H^{\pm\pm} \rightarrow \mu\tau) = 1$$

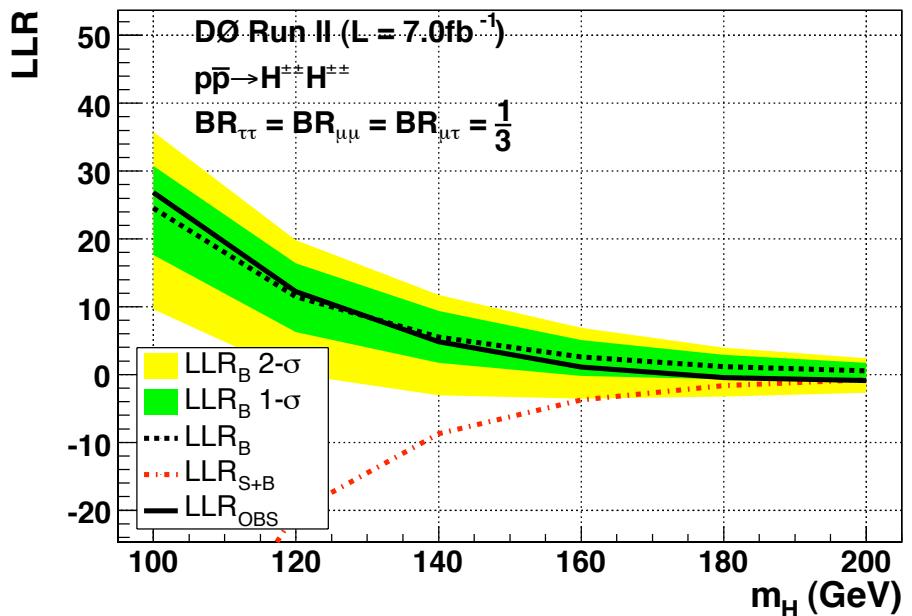
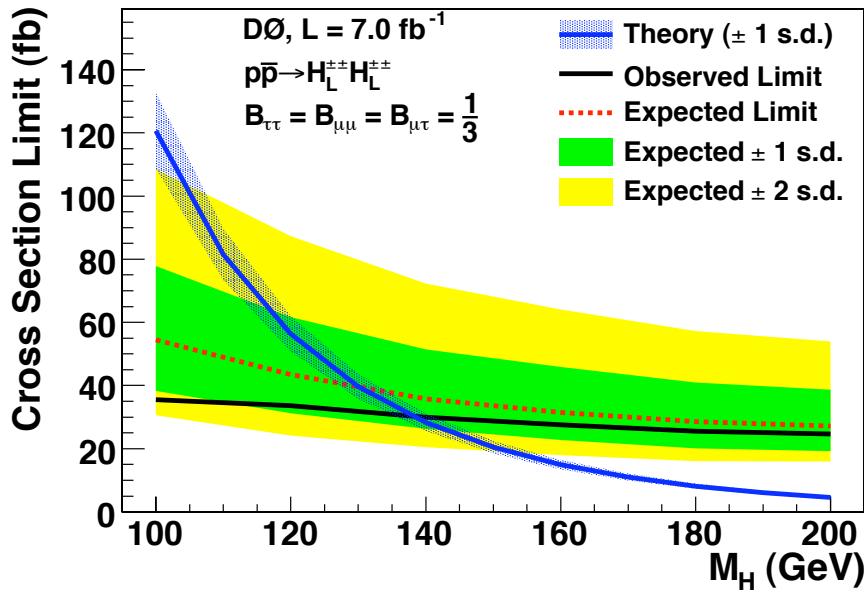


Left  
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Right  
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# $H^{\pm\pm}$ limits: Benchmark 5

$$B(H^{\pm\pm} \rightarrow \tau\tau) = B(H^{\pm\pm} \rightarrow \mu\mu) = B(H^{\pm\pm} \rightarrow \mu\tau) = \frac{1}{3}$$



Benchmark point specific to Little Higgs models where no right handed  $H^{\pm\pm}$

# $H^{\pm\pm}$ mass exclusion summary

BP	$H^{\pm\pm}$ branching ratio	$M(H_L^{\pm\pm})$ [GeV]		$M(H_R^{\pm\pm})$ [GeV]	
		$\sigma_{exp}$ [fb]	$\sigma_{obs}$ [fb]	$\sigma_{exp}$ [fb]	$\sigma_{obs}$ [fb]
1	$B_{\tau\tau} = 1$	116	128	NS	94
	$B_{\tau\tau} = 0.9, B_{\mu\mu} = 0.1$	118	128	NS	97
	$B_{\tau\tau} = 0.8, B_{\mu\mu} = 0.2$	123	128	NS	101
	$B_{\tau\tau} = 0.7, B_{\mu\mu} = 0.3$	130	131	98	108
	$B_{\tau\tau} = 0.6, B_{\mu\mu} = 0.4$	138	135	107	112
2	$B_{\tau\tau} = 0.5, B_{\mu\mu} = 0.5$	146	139	115	117
	$B_{\tau\tau} = 0.4, B_{\mu\mu} = 0.6$	154	144	124	122
	$B_{\tau\tau} = 0.3, B_{\mu\mu} = 0.7$	160	149	132	128
	$B_{\tau\tau} = 0.2, B_{\mu\mu} = 0.8$	167	156	139	133
	$B_{\tau\tau} = 0.1, B_{\mu\mu} = 0.9$	174	161	148	138
3	$B_{\mu\mu} = 1$	180	168	154	145
4	$B_{\tau\mu} = 1$	149	144	119	113
5	Equal B	130	138	—	—

# Higgs bosons at the Tevatron



## Production Modes

- Gluon-gluon fusion

$$gg \rightarrow H$$

- Vector boson fusion

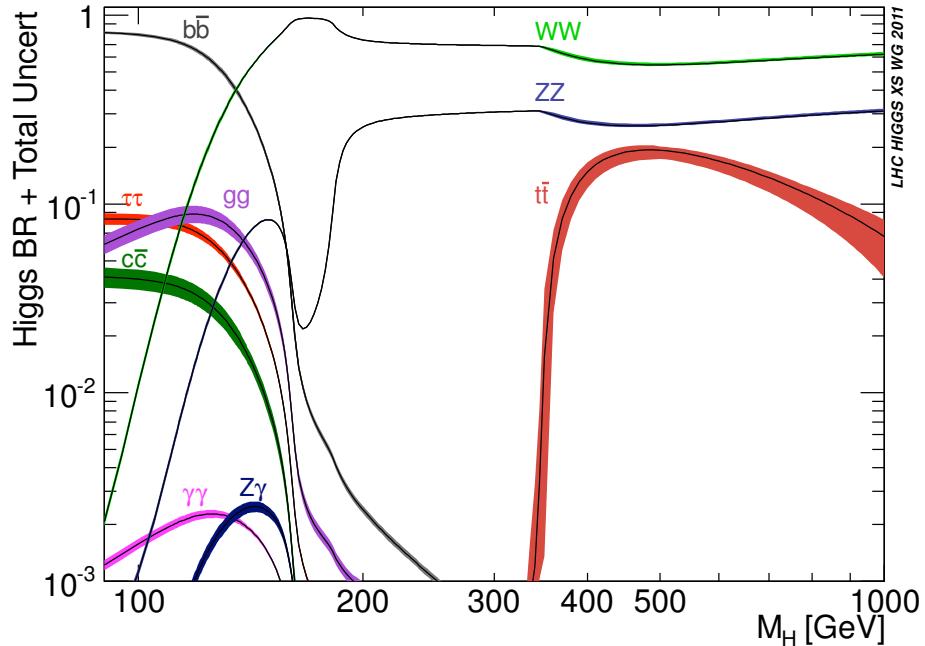
$$q\bar{q} \rightarrow q\bar{q}H$$

- Associated production

$$q\bar{q} \rightarrow Z \rightarrow ZH$$

$$q\bar{q} \rightarrow W \rightarrow WH$$

## Decay Modes



Below 120 GeV the dominant Higgs decays are to  $bb$  and  $\tau\tau$

# SM event yields

	All Types	Type-1	Type-2	Type-3
<b>Data</b>	22	2	15	5
$Z/\gamma^* \rightarrow \tau\tau$	$5.56 \pm 0.71$	$0.75 \pm 0.10$	$3.91 \pm 0.50$	$0.91 \pm 0.12$
$Z/\gamma^* \rightarrow \mu\mu$	$4.42 \pm 0.56$	$0.70 \pm 0.09$	$3.24 \pm 0.41$	$0.49 \pm 0.06$
$Z/\gamma^* \rightarrow \mu\mu$	$0.31 \pm 0.04$	$< 0.01$	$0.26 \pm 0.03$	$0.05 \pm 0.01$
$t\bar{t}$	$1.43 \pm 0.21$	$0.27 \pm 0.04$	$1.07 \pm 0.16$	$0.07 \pm 0.03$
Diboson	$9.01 \pm 1.31$	$0.41 \pm 0.06$	$7.01 \pm 0.10$	$1.58 \pm 0.23$
$W + \text{jet}$	$5.38 \pm 0.66$	$0.62 \pm 0.08$	$3.20 \pm 0.40$	$1.54 \pm 0.19$
Multijet	$< 0.47$	$< 0.04$	$< 0.32$	$< 0.11$
<b>Total Bkg</b>	$26.11 \pm 3.96$	$2.75 \pm 0.37$	$18.67 \pm 1.2$	$4.63 \pm 0.48$
<b>Signal 125 GeV</b>				
$ZH$	$0.17 \pm 0.02$	$0.02 \pm 0.002$	$0.13 \pm 0.02$	$0.02 \pm 0.002$
$WH$	$0.52 \pm 0.06$	$0.05 \pm 0.01$	$0.40 \pm 0.05$	$0.06 \pm 0.01$

# Selection criteria on BDT pass 1

$M_H$ [GeV]	100	105	110	115	120	125	130
BDT Pass 1 criteria	0.698	0.680	0.738	0.657	0.705	0.744	0.758
$M_H$ [GeV]	135	140	145	150	155	160	165
BDT Pass 1 criteria	0.736	0.750	0.704	0.763	0.783	0.694	0.746
$M_H$ [GeV]	170	175	180	185	190	195	200
BDT Pass 1 criteria	0.707	0.699	0.763	0.757	0.760	0.737	778

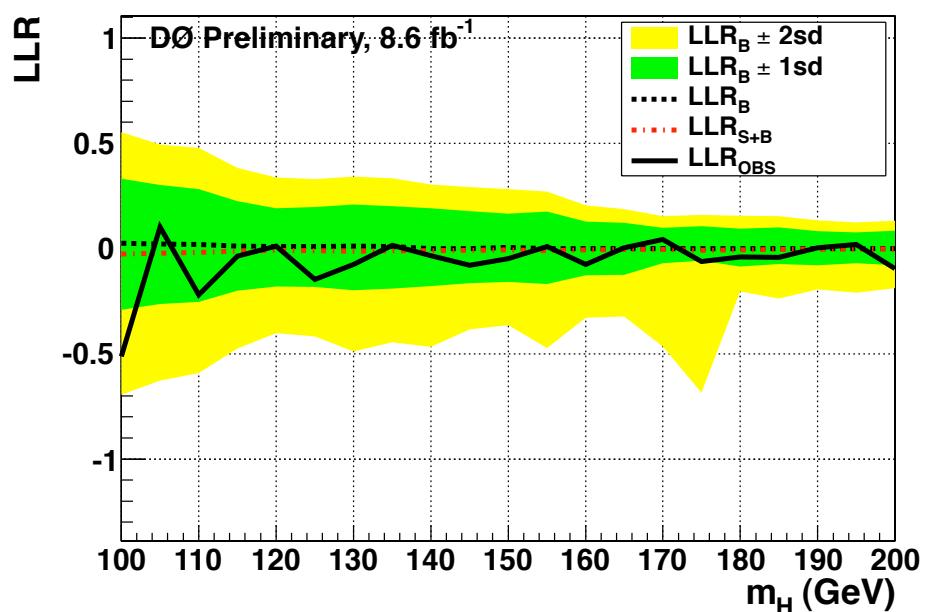
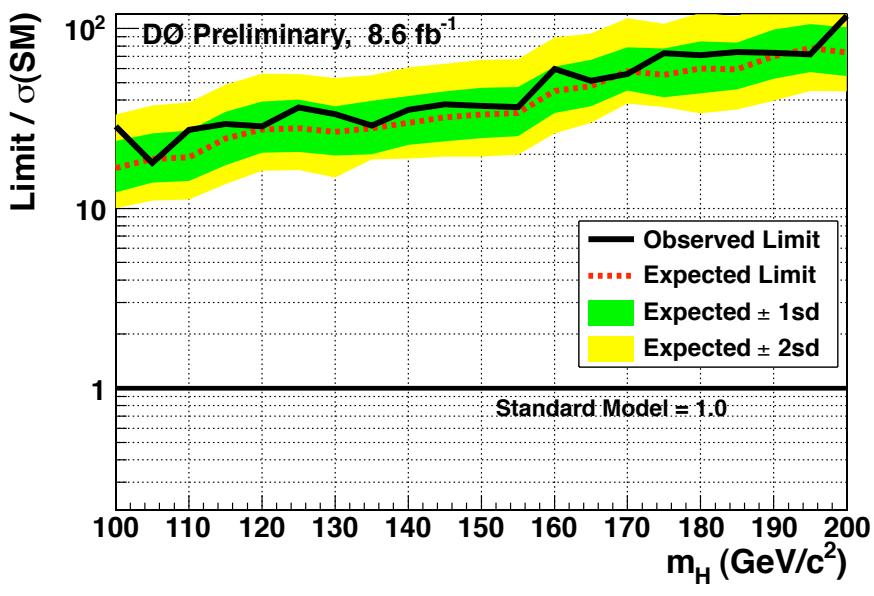
# SM event yields after BDT pass 1 requirement

Mass [GeV]	100	110	120	130	140	150
<b>Data</b>	6	3	8	5	6	6
$Z/\gamma^* \rightarrow \tau\tau$	$0.39 \pm 0.05$	$0.11 \pm 0.01$	$0.47 \pm 0.06$	$0.25 \pm 0.03$	$0.41 \pm 0.05$	$0.22 \pm 0.03$
$Z/\gamma^* \rightarrow \mu\mu$	$0.70 \pm 0.09$	$0.43 \pm 0.05$	$0.71 \pm 0.09$	$0.94 \pm 0.12$	$0.43 \pm 0.05$	$0.68 \pm 0.09$
$Z/\gamma^* \rightarrow \mu\mu$	$0.13 \pm 0.02$	$0.13 \pm 0.02$	$0.10 \pm 0.01$	$0.11 \pm 0.01$	$0.08 \pm 0.01$	$0.12 \pm 0.02$
$t\bar{t}$	$0.71 \pm 0.10$	$0.58 \pm 0.08$	$0.71 \pm 0.10$	$0.67 \pm 0.10$	$0.76 \pm 0.11$	$0.67 \pm 0.10$
Diboson	$5.25 \pm 0.67$	$4.58 \pm 0.58$	$5.61 \pm 0.71$	$5.15 \pm 0.66$	$4.82 \pm 0.61$	$4.61 \pm 0.59$
$W + \text{jet}$	$0.37 \pm 0.05$	$0.57 \pm 0.07$	$0.39 \pm 0.05$	$0.29 \pm 0.04$	$0.27 \pm 0.03$	$0.42 \pm 0.05$
<b>Total Bkg</b>	$7.54 \pm 0.98$	$6.41 \pm 0.81$	$7.99 \pm 1.01$	$7.41 \pm 0.96$	$6.79 \pm 0.86$	$6.73 \pm 0.98$
<b>Signal</b>						
$ZH$	$0.11 \pm 0.01$	$0.09 \pm 0.01$	$0.11 \pm 0.01$	$0.10 \pm 0.01$	$0.12 \pm 0.01$	$0.09 \pm 0.01$
$WH$	$0.43 \pm 0.05$	$0.32 \pm 0.04$	$0.31 \pm 0.04$	$0.23 \pm 0.03$	$0.21 \pm 0.03$	$0.17 \pm 0.02$

# SM event yields after BDT pass 1 requirement

Mass [GeV]	160	170	180	190	200
<b>Data</b>	7	5	6	7	4
$Z/\gamma^* \rightarrow \tau\tau$	$0.27 \pm 0.03$	$0.19 \pm 0.02$	$0.20 \pm 0.03$	$0.22 \pm 0.03$	$0.20 \pm 0.03$
$Z/\gamma^* \rightarrow \mu\mu$	$0.61 \pm 0.78$	$0.41 \pm 0.05$	$0.34 \pm 0.04$	$0.37 \pm 0.05$	$0.60 \pm 0.07$
$Z/\gamma^* \rightarrow \mu\mu$	$0.10 \pm 0.01$	$0.09 \pm 0.01$	$0.06 \pm 0.01$	$0.16 \pm 0.02$	$0.14 \pm 0.02$
$t\bar{t}$	$0.91 \pm 0.13$	$0.88 \pm 0.13$	$0.73 \pm 0.11$	$0.79 \pm 0.12$	$0.76 \pm 0.11$
Diboson	$4.47 \pm 0.60$	$4.67 \pm 0.60$	$3.98 \pm 0.51$	$4.73 \pm 0.60$	$4.47 \pm 0.57$
$W + \text{jet}$	$0.18 \pm 0.02$	$0.75 \pm 0.10$	$0.51 \pm 0.07$	$0.40 \pm 0.05$	$0.38 \pm 0.05$
<b>Total Bkg</b>	$6.53 \pm 1.57$	$6.89 \pm 0.91$	$5.82 \pm 0.77$	$6.67 \pm 0.87$	$6.54 \pm 0.85$
<b>Signal</b>					
$ZH$	$0.10 \pm 0.01$	$0.08 \pm 0.01$	$0.07 \pm 0.01$	$0.06 \pm 0.01$	$0.05 \pm 0.01$
$WH$	$0.18 \pm 0.02$	$0.17 \pm 0.02$	$0.12 \pm 0.01$	$0.11 \pm 0.01$	$0.09 \pm 0.01$

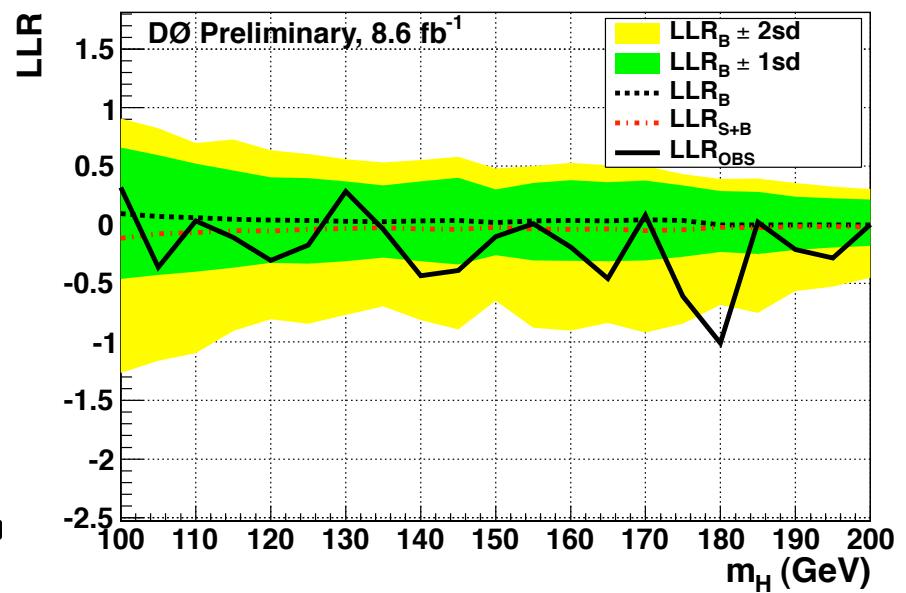
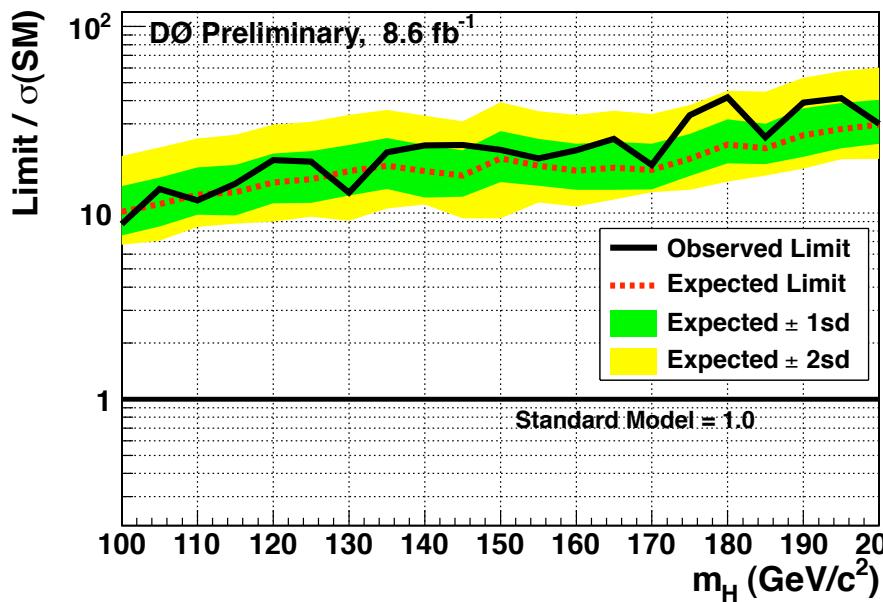
# SM cross section limits BDT pass 1



# SM cross section limits BDT pass 1

$M_H$ [GeV]	100	105	110	115	120	125	130
$\sigma_{exp}/\sigma_{exp}(SM)$	16.8	18.8	19.2	24.4	27.4	27.9	26.6
$\sigma_{obs}/\sigma_{obs}(SM)$	28.6	17.9	27.3	29.5	28.6	36.3	33.4
$M_H$ [GeV]	135	140	145	150	155	160	165
$\sigma_{exp}/\sigma_{exp}(SM)$	27.8	29.9	32.1	33.2	33.9	45.1	47.9
$\sigma_{obs}/\sigma_{obs}(SM)$	28.9	35.3	37.9	37.2	36.6	59.7	51.3
$M_H$ [GeV]	170	175	180	185	190	195	200
$\sigma_{exp}/\sigma_{exp}(SM)$	52.0	48.2	55.9	55.3	66.8	71.4	68.7
$\sigma_{obs}/\sigma_{obs}(SM)$	50.2	59.6	64.9	64.9	68.2	67.7	99.7

# SM cross section limits BDT pass 2

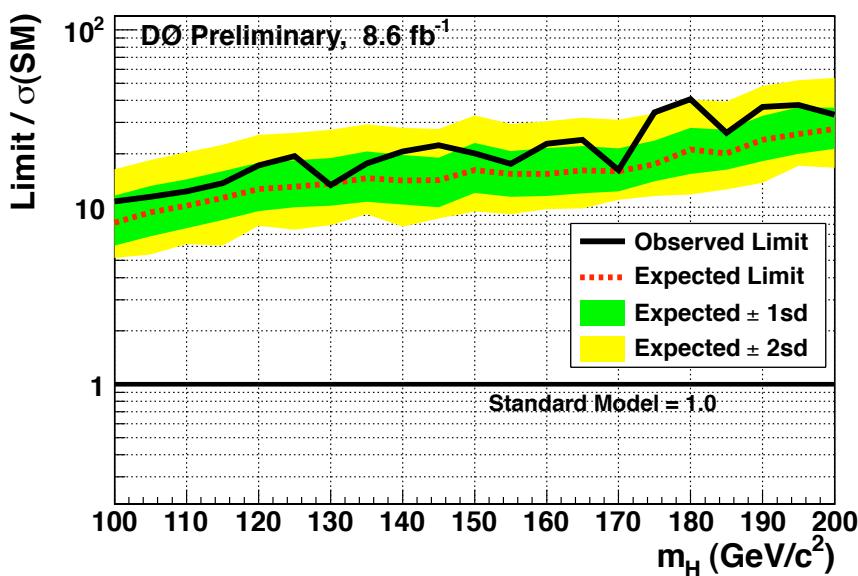


# SM cross section limits BDT pass 2

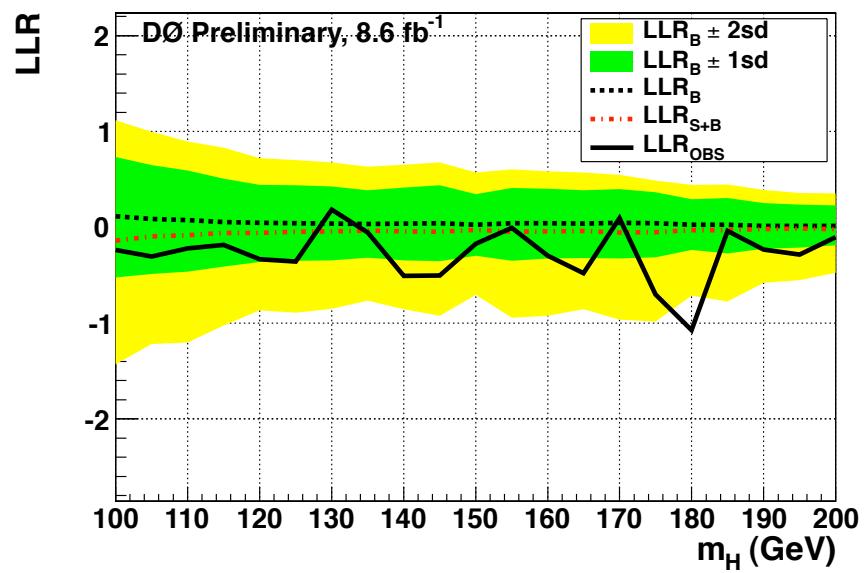
$M_H$ [GeV]	100	105	110	115	120	125	130
$\sigma_{exp}/\sigma_{exp}(SM)$	10.1	11.1	12.5	12.9	14.6	15.1	16.8
$\sigma_{obs}/\sigma_{obs}(SM)$	8.7	13.4	11.7	14.4	19.2	18.8	12.8
$M_H$ [GeV]	135	140	145	150	155	160	165
$\sigma_{exp}/\sigma_{exp}(SM)$	17.9	16.8	15.9	19.6	17.9	16.8	17.5
$\sigma_{obs}/\sigma_{obs}(SM)$	21.2	23.0	23.2	21.8	19.6	21.6	24.9
$M_H$ [GeV]	170	175	180	185	190	195	200
$\sigma_{exp}/\sigma_{exp}(SM)$	17.0	19.5	23.3	22.2	26.1	28.2	29.8
$\sigma_{obs}/\sigma_{obs}(SM)$	18.1	33.5	41.7	25.4	39.1	41.4	30.11

# SM cross section limits combined

95% C.L. limits



Log-likelihood ratio



Both BDT pass 2 and the region of BDT pass 1 that fail the background rejection requirement are combined to set cross section limits as ratio to SM Higgs cross section

# SM cross section limits combined

$M_H$ [GeV]	100	105	110	115	120	125	130
$\sigma_{exp}/\sigma_{exp}(SM)$	8.2	9.3	10.2	11.3	12.7	13.0	13.5
$\sigma_{obs}/\sigma_{obs}(SM)$	10.8	11.4	12.3	13.6	17.2	19.4	13.3
$M_H$ [GeV]	135	140	145	150	155	160	165
$\sigma_{exp}/\sigma_{exp}(SM)$	14.6	14.1	14.2	16.2	15.4	15.4	16.1
$\sigma_{obs}/\sigma_{obs}(SM)$	17.6	20.6	22.3	20.1	17.6	22.8	23.9
$M_H$ [GeV]	170	175	180	185	190	195	200
$\sigma_{exp}/\sigma_{exp}(SM)$	16.0	17.4	21.1	20.1	24.0	25.9	27.5
$\sigma_{obs}/\sigma_{obs}(SM)$	16.2	34.3	40.7	26.2	36.7	37.8	33.3